ORIGINAL ARTICLE

Correlation of Laparoscopic Experience With Differential Functional Brain Activation

A Positron Emission Tomography Study With Oxygen 15–Labeled Water

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Hypothesis: Regions of functional brain activation differ between novice and expert laparoscopists.

Design: We compared novice and expert laparoscopists using positron emission tomography (PET) during the peg transfer task of the McGill Inanimate System for Training and Evaluation of Laparoscopic Skills (MISTELS) protocol. The first scan (rest) was performed with the subject's eyes closed. The second scan (video 1) was performed while watching a peg transfer video. The third scan (peg 1) was acquired during the peg transfer task. The forth scan (peg 2) was performed after practicing 15 minutes. The fifth scan (video 2) was performed after peg 2 as the subject watched a video clip of a laparoscopic partial nephrectomy. The sixth scan (peg 3) was conducted during the final peg transfer task after 15 more minutes of practice.

Setting: Feinstein Institute for Medical Research.

Participants: Five novice and 5 expert laparoscopists.

Main Outcome Measures: Differences in brain activation as determined by changes in regional cerebral blood flow on PET scans with oxygen 15–labeled water.

Results: The first analysis examined group differences between the 3 peg scans and the rest scan. The novice group had a significantly ($P < .001$) higher activation (with deactivation in the expert group) in the left precentral gyrus and insula and the right precuneus and inferior occipital gyrus. The second analysis compared the 2 video scans and the rest scan. In contrast to the expert group, the novices had significantly ($P < .001$) higher activation in the right precuneus and cuneus but deactivation in the bilateral posterior cerebellum.

Conclusions: This study demonstrates differential regional brain activation patterns between novice and expert laparoscopists during surgery-related motor and visual association tasks.

Arch Surg. 2012;147(7):627-632

THE ADVENT OF LAPAROSCOPY has revolutionized many procedures across the surgical subspecialties. Multiple large studies have evaluated the risks and benefits of laparoscopic renal operations compared with open surgical procedures. Results have consistently shown that laparoscopic procedures minimize patient discomfort, operative blood loss, and length of hospital stay and speed a return to normal activity.[1,2] More importantly, these advantages can be actualized while preserving and in some cases improving overall surgical and oncologic outcomes.

Despite the clear advantages of the laparoscopic surgical procedure, several obstacles preclude its universal application. Laparoscopy is associated with a loss of depth perception owing to the 2-dimensional image, while requiring bimanual dexterity and hand-eye dissociation. In addition, the laparoscopic surgeon needs to adapt to the loss of tactile sensation and the fulcrum effect associated with the use of longer instruments. All of these factors translate into a steep learning curve for inexperienced laparoscopic surgeons. Depending on the difficulty of the procedure, it can take as many as 80 cases to attain proficiency.[3,4] A direct correlation exists between experience and the realization of laparoscopy's potential advantages. This experience would ideally be accrued outside the operating room.

Many training modalities have been developed to educate surgical residents in laparoscopy. These modalities include virtual-reality trainers, animal models, cadavers, and inanimate box systems (pelvic trainers). Several studies have shown that simulator use improves performance in the operating room.[5] The most widely used laparoscopic skill assessment tool is the McGill Inanimate System for Training and

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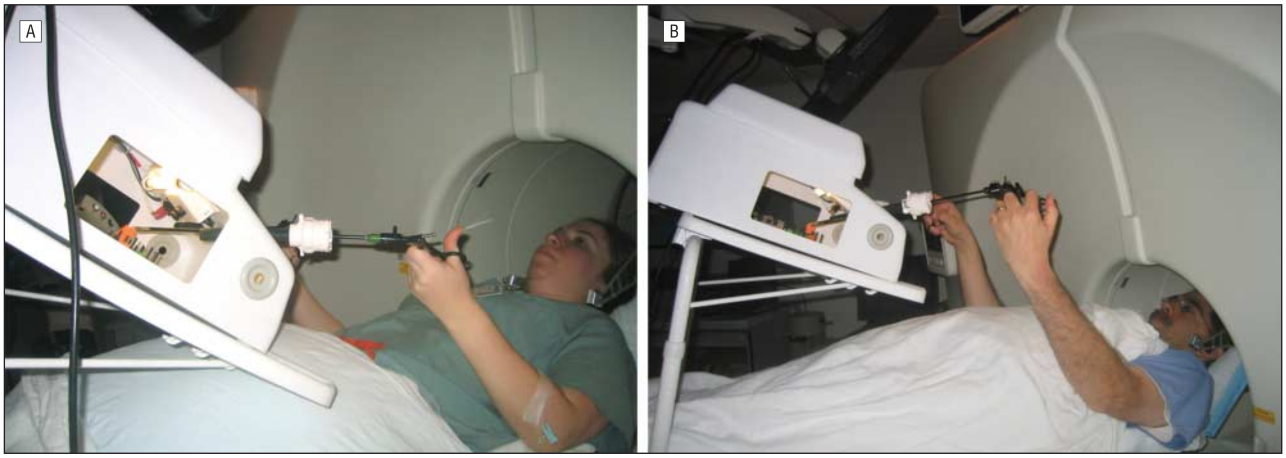

Figure 1. Experimental setup for positron emission tomography (PET). A novice subject (A) and an expert subject (B) are positioned on the PET scanner table.

Evaluation of Laparoscopic Skills (MISTELS). The MISTELS protocol has been studied extensively and has been shown to be internally consistent and reproducible by evaluating interrater and test-retest differences.[6,7] In fact, the MISTELS test has been adopted by the Society of American Gastrointestinal and Endoscopic Surgeons for its Fundamentals of Laparoscopic Skills program. Although many of the initial studies were performed in the field of general surgery, the MISTELS test has recently been shown to be valid for urologic procedures.[8]

No laparoscopic skill assessment tool has been studied in terms of functional changes in the brain. The aim of the present study was to correlate functional brain activation with the degree of laparoscopic experience by measuring changes in regional cerebral blood flow and metabolism using positron emission tomography (PET) with oxygen 15 (^{15}O)–labeled water. The procedure used a paradigm previously established for brain activation studies of motor sequence learning in human subjects.[9]

METHODS

STUDY SUBJECTS

Subjects were recruited after approval from the North Shore–Long Island Jewish Health System institutional review board (No. 07-106). Women who were pregnant, attempting to become pregnant, or breastfeeding were excluded from the study. In addition, any subject with a known neurologic defect was excluded.

All subjects were right-handed to eliminate handedness as a confounding factor. Five fourth-year medical students (4 women and 1 man) with no laparoscopic experience constituted the novice group. Their ages ranged from 25 to 27 (mean, 26.2) years. We also recruited 5 fellowship-trained minimally invasive laparoscopic urologic surgeons (all men). Their ages ranged from 35 to 55 (mean, 42.6) years.

STUDY DESIGN

All subjects fasted overnight to avoid confounding factors, such as glucose metabolism and caffeine stimulation. After insertion of an intravenous line within the left forearm, subjects were positioned supine on the PET scanner table. The head was secured with a holder (Laitinen stereoadapter; Sandstrom Trade and Technology) to prevent movement during the study. A reclining table held the laparoscopic trainer containing the pegs for the peg transfer task. A gooseneck camera mounted within the laparoscopic trainer projected a video image onto a screen that was placed above the box. The table height was adjusted for each subject to achieve the most comfortable position relative to the screen and laparoscopic instruments (**Figure 1**).

After daily calibration of the PET scanner, all subjects underwent 6 PET scans consecutively with ^{15}O-labeled water injections. The following scans were obtained: rest (task: eyes closed while holding laparoscopic instruments); video 1 (task: subjects watched a 2-minute clip of how to execute the peg transfer task); peg 1 (task: first peg transfer without any practice); peg 2 (task: second peg transfer after 15 minutes of practice); video 2 (task: subjects watched a 2-minute clip of a laparoscopic partial nephrectomy); and peg 3 (task: third peg transfer after 15 more minutes of practice).

Observation and task performance have been shown to facilitate acquisition of complex motor skills.[10,11] Therefore, both learning components were incorporated into the study protocol. Video 1 illustrated the peg transfer protocol and demonstrated a simple laparoscopic task. In contrast, video 2 was included to illustrate a complex procedure requiring advanced laparoscopic skills. Laparoscopic partial nephrectomy was chosen because the expert group consisted of urologists with special training in laparoscopic renal surgery. None of the novice subjects had seen the procedure before. Performance-based learning was assessed by the 3 repetitions of the peg transfer task.

PEG TRANSFER TASK AND CALCULATION OF NORMALIZED SCORES

The MISTELS peg transfer task was used in the present study. The peg transfer task requires each subject to transfer 3 pegs from the right to the left hand and then place the pegs onto pins. The pegs are then removed from the pins using the left hand, transferred back to the right hand, and finally placed back onto the pins using the right hand. This sequence is then repeated, thereby completing the task. Each subject was timed using a stopwatch to calculate the number of seconds required to complete the task. Subjects were penalized for dropped pegs. The final normalized scores were calculated using the following equations:

$$\text{Time (in seconds)} = 300 - \text{Time Required to Complete Task (in seconds)}$$

$$\text{Penalty} = (\text{Peg not Transferred}/3) \times 100$$

$$\text{Raw Score} = \text{Time} - \text{Penalty}$$

$$\text{Normalized Score} = \text{Raw Score}/237 \times 100$$

The normalization score has been validated by Vassiliou et al.[6] After the calculation, the 2-tailed t test was used to compare the novice group with the expert group.

PET SCANNING

The PET scans were acquired using a commercially available device (GE Advance Tomograph; GE Medical Systems) at the Feinstein Institute for Medical Research. The performance characteristics of this instrument have previously been described in the literature.[12] This 18-ring bismuth germanate scanner provides 35 image planes with an axial field of view of 14.5 cm. Transaxial resolution is 3.8 mm (full-width at half maximum) at the center. Quantitative PET studies were performed in the 3-dimensional mode.

As much as 12 mCi of ^{15}O-labeled water in 3 mL of saline was injected by an automatic pump within 30 seconds (6 mL/min), followed by an automatic 3-mL saline flush (to convert millicuries to megabecquerels, multiply by 37). A sudden increase in the count rate determined when the bolus had entered the brain. The tasks were timed so that the radioactive tracer arrived to the brain approximately 10 seconds after the initiation of the task. Dynamic 3-dimensional PET data acquisition was then performed at the time of radioactivity arrival to the brain and continued for a total of 90 seconds. The end of the task coincided with the end of data acquisition. Reconstructed PET images were corrected for tissue attenuation (by a separate 10-minute transmission scan) and for random coincidences and electronic dead time. A single scalar correction was used to compensate for scatter effects.

The same procedure was repeated for all remaining scans, with a 7-minute minimum interval between each scan. Owing to the short half-life of the tracer ($t_{1/2}$=2 minutes) and the short scanning time, each subject could safely undergo a total of 10 scans, well within the allowable total radiation dose. None of the subjects required the maximum allowed 10 injections.

DATA ANLAYSIS

We analyzed the PET scans to determine differences in regional blood flow after task performance (the average of the 3 peg scans vs the rest scan) and laparoscopic skill observation (the average of the 2 video scans vs the rest scan). Brain activation data were analyzed using statistical parametric mapping software (Wellcome Department of Cognitive Neurology, Institute of Neurology) (MATLAB-based program [MathWorks] running on personal computers with Windows XP [Microsoft Corp]). All PET scans were spatially normalized and smoothed with a 15-mm gaussian filter in 3 dimensions. We performed 1-way repeated-measures analysis of variance in each subject group to identify functional response patterns in different brain regions. Brain regions with overall mean differences between the expert and novice subjects were identified using post hoc contrast tests implemented in the statistical parametric mapping software. We then used the PET scans with ^{15}O-labeled water to correlate differences in cerebral blood flow to determine the effects of observation and task performance on brain function in the novice and expert groups.

Between-group differences in cerebral blood flow were considered significant at $t>3.31$ ($P<.001$) and with an extent threshold of 30 voxels (corresponding to a tissue volume of 240 mm^3). The t maps showing different brain activation between the groups were overlaid on a standard magnetic resonance imaging brain template. Regional differences in cerebral blood flow were also measured with a spherical volume of interest (radius=4 mm) centered at the peak voxel of each significant cluster. An increase in this value usually reflected brain activation of a task condition relative to the rest scan, whereas a decrease in this value was generally considered brain deactivation under the task condition.

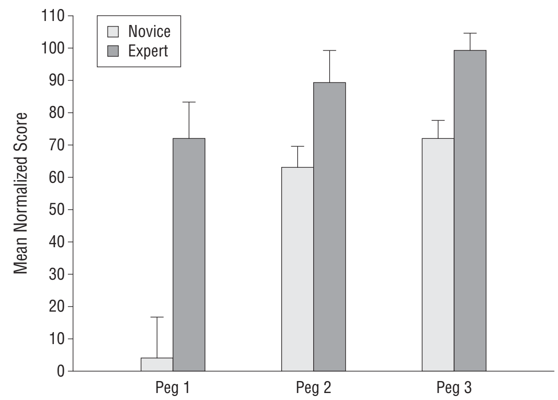

Figure 2. Normalized scores of the peg transfer tasks for the novice and expert groups.

RESULTS

MISTELS NORMALIZED SCORES

The novice group had significantly lower normalized mean scores than the expert group on the peg tasks (46.2 vs 86.6; P=.001). This finding confirmed objectively that a significant difference existed in the laparoscopic skill level between the 2 groups. The novice group's normalized scores improved from 3.9 to 62.9 (P=.006) after 15 minutes of practice. The scores improved further to 71.8 after a second practice session. However, we found no significant difference between the second and third peg transfer normalized scores. For the expert group, the normalized scores improved from 71.8 to 89.1 to 99.1 in pegs 1, 2, and 3, respectively. However, differences among these improvements were not statistically significant (**Figure 2**).

PET IMAGE ANALYSIS

The first image analysis examined group differences between the average of the 3 peg scans (pegs 1, 2, and 3) and the rest scan. The main findings are summarized in **Table 1** and **Figure 3**. When compared with the expert group, the novice group had a significantly ($P<.001$) higher activation in the left precentral gyrus and insula and in the right precuneus and inferior occipital gyrus. The apparent difference between the 2 groups actually resulted from activation in the novice group and deactivation in the expert group within these brain regions, as evidenced in the corresponding post hoc volume-of-interest plots. However, we found no regions of decreased activation in the novice group compared with the expert laparoscopists.

The second image analysis evaluated group differences between the average of the 2 video scans (videos 1 and 2) and the rest scan. The principal findings are shown in **Table 2** and **Figure 4**. The novice group had significantly increased activation ($P<.001$) in the right pre-

Table 1. Neuroanatomical Regions With Significant Task-Specific Differences in CBF Between the Novice and Expert Groups During the Peg Transfer Task Scan vs the Rest Scan[a]

CBF	Brain Region	Side	Size, No. of Voxels[a]	MNI Coordinate x	MNI Coordinate y	MNI Coordinate z	*t* Value
Novice > expert	Frontal, precentral gyrus	L	154	−56	−2	40	5.1
	Occipital, inferior occipital gyrus	R	173	26	−100	−18	4.9
	Occipital, precuneus	R	39	6	−74	28	4.6
	Sublobar, insula	L	89	−42	−18	14	4.4

Abbreviations: CBF, cerebral blood flow; L, left; MNI, Montreal Neurological Institute; R, right.
[a]The size of each voxel is $2 \times 2 \times 2$ mm³.

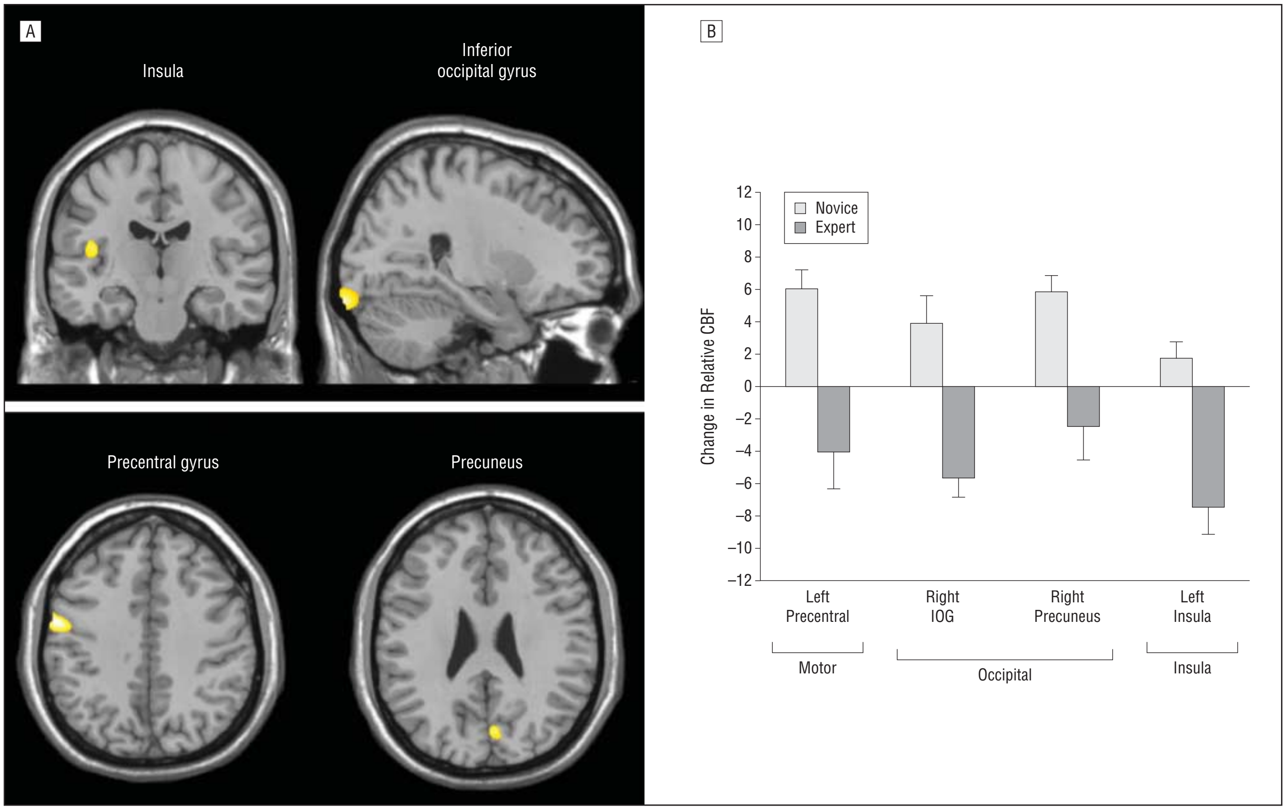

Figure 3. Comparison between the novice and expert groups during the performance of peg transfer tasks. A, The task-specific differences in cerebral blood flow (CBF) between subject groups are overlaid on a standard magnetic resonance imaging brain template. Yellow areas indicate increased CBF thresholded at $t > 3.31$ ($P < .001$). B, The regional differences in CBF between the 2 subject groups are represented as mean (SEM). IOG indicates inferior occipital gyrus.

Table 2. Neuroanatomical Regions With Significant Task-Specific Differences in CBF Between the Novice and Expert Groups During the Video Task Scans vs the Rest Scan

CBF	Brain Region	Side	Size, No. of Voxels[a]	MNI coordinate x	MNI coordinate y	MNI coordinate z	*t* Value
Novice > expert	Occipital, precuneus	R	62	6	−74	26	5.00
	Occipital, cuneus	R	89	12	−66	6	4.25
Novice < expert	Posterior cerebellum, declive	L	120	−14	−74	−28	4.67
	Posterior cerebellum, uvula	R	157	24	−74	−34	4.55

Abbreviations: CBF, cerebral blood flow; L, left; MNI, Montreal Neurological Institute; R, right.
[a]The size of each voxel is $2 \times 2 \times 2$ mm³.

cuneus and cuneus relative to the expert group. We attributed this increase to activation in the former group but deactivation in the latter group within the occipital cortex. In contrast, the novice group showed significant deactivation ($P < .001$) in the bilateral posterior cerebellum compared with the expert group. This decrease in-

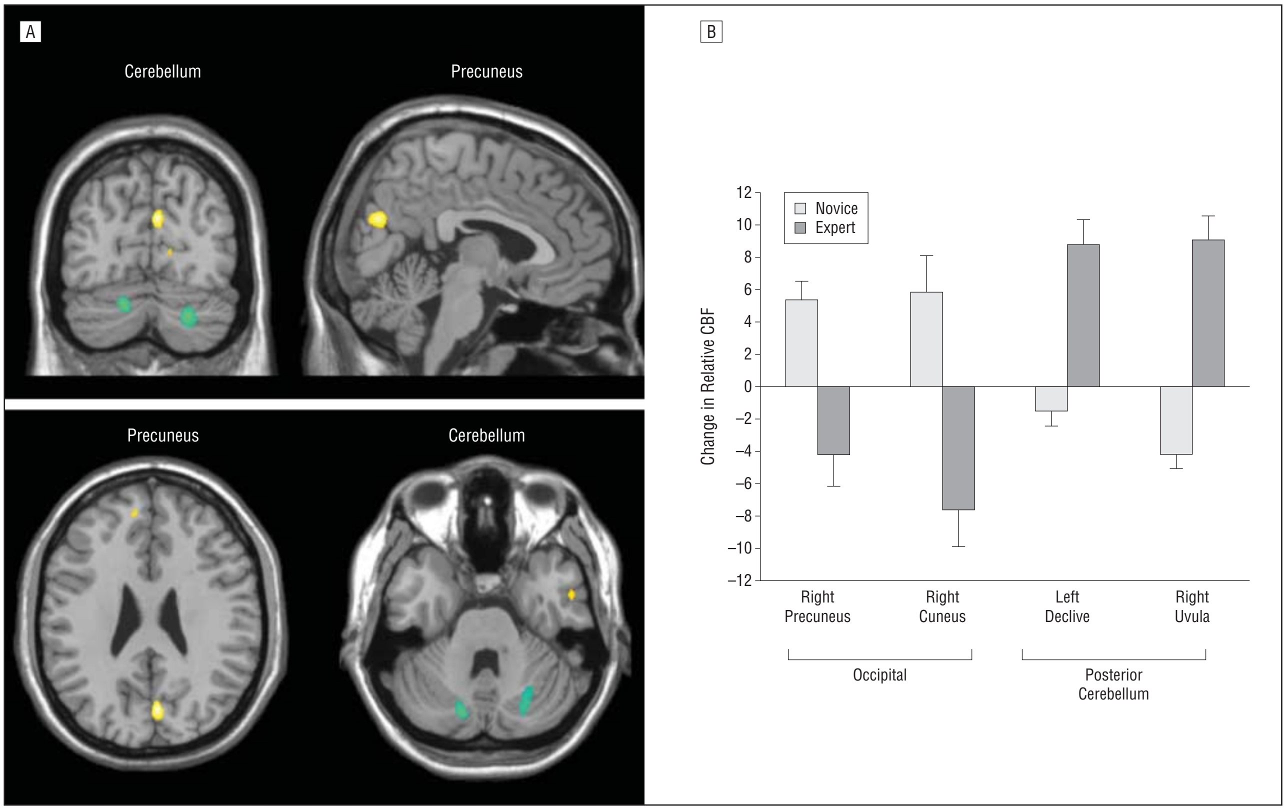

Figure 4. Comparison between the novice and expert groups during the performance of video review tasks. A, The task-specific differences in cerebral blood flow (CBF) between subject groups are overlaid on a standard magnetic resonance imaging brain template. Yellow areas indicate increased CBF; green areas, decreased CBF. Both areas are thresholded at $t > 3.31$ ($P < .001$). B, The regional CBF differences between the 2 subject groups are represented as mean (SEM).

dicated deactivation in the novice group but activation in the expert group within the cerebellum. The region-specific differences in the magnitude of activation or deactivation were visible in the corresponding post hoc volume-of-interest plots.

COMMENT

The use of PET makes it possible to localize specific regions in the brain that are activated while performing psychomotor tasks. Localization is accomplished by real-time measurement of cerebral blood flow as an indicator of parenchymal metabolism. The purpose of this pilot study was to correlate functional brain activation with the degree of laparoscopic experience by measuring changes in regional cerebral blood flow using PET with ^{15}O-labeled water during surgery-related motor and visual association tasks.

As expected, the 2 groups differed significantly in their initial peg transfer normalized scores. However, the novice group's normalized scores improved after 2 practice sessions to the initial level of the expert laparoscopists, despite the expert group having many more years of laparoscopic experience compared with the novice subjects, who had no prior exposure to laparoscopy. This finding reflects the poor ability of low-complexity tasks, such as the peg transfer drill, to differentiate between individuals with varying laparoscopic skill after a practice period.

Although the MISTELS test has been shown to correlate with subjective assessment on in-training surgical evaluations, it has a number of limitations.[13] First, the test assesses gross laparoscopic motor skill only. As such, scoring well on the test is not necessarily synonymous with being a better laparoscopic surgeon.[13] Second, the MISTELS test cannot determine the cognitive component of surgical skill. Being able to address unusual anatomy and to handle intraoperative complications appropriately are hallmarks of an expert surgeon. Last, the MISTELS test does not account for economy of movement.

Despite narrowing of normalized scores between the 2 groups, we noted significant differences in brain activation between the novices and experts. These findings most likely reflect the process of consolidation, which takes newly acquired motor skills and transfers them into a more stable state over time. Behavioral and neuroimaging studies have demonstrated that consolidated motor tasks are performed by different regions of the brain compared with newly learned motor skills.[14]

In contrast to the expert laparoscopists, the novice group exhibited significantly greater activation of the insula, precuneus, and inferior occipital gyrus after the peg transfer task. These regions of the brain have been shown to be involved in motor and visuospatial learning.[15] The left middle frontal gyrus was also activated. This region of the brain is believed to be involved in implicit learning. Therefore, we can conclude that the novice laparoscopists were using this region of the brain to coordinate learning the peg transfer motor task. The expert group had already consolidated the laparoscopic skills needed to perform the peg transfer. Hence, the experienced laparoscopists used only the regions of the motor cortex required to activate muscle movement for task completion.

Differences in regional blood flow were also noted after laparoscopic skill observation (videos 1 and 2). The inexperienced group exhibited greater activation of the occipital lobe, whereas the expert cohort was found to have increased blood flow to the posterior cerebellum. Not surprisingly, the novice group, which had never seen a laparoscopic partial nephrectomy before, had greater activation of the visual cortex. We noted increased activation of the cerebellum in the expert group. The cerebellum has been shown to assume a prominent role once motor tasks have been consolidated.[15]

Previous functional neuroimaging studies have shown similar differential patterns of brain activation when performing a novel motor task and when performing the same task after a period of practice.[16] During performance of a novel, simple motor task (maze and square tracing tasks), van Mier and colleagues[16] noted activation of the right dorsal premotor area, right inferior and superior parietal regions, and left lateral cerebellum. After practice, the authors found the pattern of activation changed, with activity in the supplementary motor area being associated with skilled performance. Similar findings were noted in a study of pianists and nonmusicians asked to perform complex movement sequences on a keyboard.[11]

The ultimate goal of this study was to better understand the neural networks involved in learning laparoscopic surgical skills, which may benefit the medical community by improving surgeon education and assessment. Imaging with PET could be used to differentiate individuals who have recently practiced a particular task from those who have previously mastered the task. Specifically, functional brain imaging may provide an objective method of comparing the cognitive processes of novice and expert surgeons, thereby improving the utility of the MISTELS protocol in evaluating laparoscopists. In addition, improved understanding of the neural pathways used to master surgical tasks may aid in the development of training devices that are designed to target known areas of the brain associated with skill acquisition.

Future investigations need to recruit more novice and expert laparoscopists to validate the present study's results. Furthermore, subjects with intermediate levels of laparoscopic experience, such as senior surgical residents, could undergo testing to determine when the regions of the brain involved in motor and visuospatial learning cease to be activated and only motor cortical activation dominates.

The present study has several limitations. First, 4 of the 5 novice subjects were women, and all 5 experts were men. The changes observed between the 2 groups may be attributed to sex differences. Ideally, each group should have consisted of an equal number of men and women. Similarly, the average age of the novice subjects was 26.2 years, whereas the average age of the expert subjects was 42.6 years. This difference is because novice subjects were medical students with no laparoscopic exposure and the experts were laparoscopic attending surgeons. Again, the differences observed in the present study may be attributed to the age difference. Ideally, a group of attending surgeons with no laparoscopic exposure could undergo evaluation to determine whether the differences observed are truly the result of inexperience vs age-related changes in cerebral blood flow.

Accepted for Publication: November 16, 2011.
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Financial Disclosure: None reported.
Funding/Support: This study was supported by grant M01 RR018535 from the General Clinical Research Center of the Feinstein Institute for Medical Research and by an award to Dr Andonian from the Quebec Urological Association Foundation.

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