

# The frontal cortex is activated during learning of endoscopic procedures

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## Abstract

**Background** To date, several training and evaluation systems for endoscopic surgery have been developed, such as virtual-reality simulators and box trainers. However, despite current advances in these objective assessments, no functional brain studies during learning of endoscopic surgical skills have been carried out. In the present study, we investigated cortical activation using near-infrared spectroscopy (NIRS) during endoscopic surgical tasks.

**Study design** A total of 21 right-handed subjects, comprising 4 surgical experts, 4 trainees, and 13 novices, participated in the study. Suturing and knot-tying tasks were performed in a box trainer. Cortical activation was assessed in all subjects by task-related changes in hemoglobin (Hb) oxygenation using NIRS.

**Results** In surgical experts and novices with no experience of endoscopic surgical training, we found no changes in oxy-Hb, deoxy-Hb or total-Hb levels in any of the frontal channels. In surgical trainees and one novice with experience of endoscopic surgical training, we found significant increases in oxy-Hb and total-Hb levels in most of the frontal channels. There were significant differences in oxy-Hb and total-Hb levels in CH-19 between surgical experts and trainees ( $p = 0.02$  for both), and between surgical trainees and novices with no experience of endoscopic surgical training ( $p = 0.008$  for both). Furthermore, additional training increased oxy-Hb levels in the frontal cortex of novices with no experience of endoscopic surgical training but had no such effect on surgical experts.

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**Conclusions** The present data suggest that NIRS is a feasible tool for assessing brain activation during endoscopic surgical tasks, and may have a large impact on the future development of teaching, training, and assessment methods for endoscopic surgical skills.

**Keywords** Near-infrared spectroscopy (NIRS) · Endoscopic surgery · Cortical activation · Suturing and knot tying

### Abbreviations

NIRS Near-infrared spectroscopy  
Hb Hemoglobin

The indications for endoscopic intervention are constantly expanding, and endoscopic surgery is currently the standard for an increasing number of operations. Advances in endoscopic surgery have led to less postoperative pain, shorter hospital stays, and earlier return to work for many patients. However, performing endoscopic procedures requires several skills that have never been required for conventional open surgery. One of these skills is eye–hand coordination within a three-dimensional scene observed on a two-dimensional display. Access is also limited as the surgery is performed with long forceps inserted through trocars in the abdominal wall. These factors increase the difficulties associated with endoscopic surgery. There is therefore no doubt that endoscopic training for surgeons is very important to reduce fatal accidents arising through inexperience and poor technique. To date, several training methods for endoscopic surgery have been developed. Virtual-reality surgical simulators and box trainers that incorporate conventional endoscopic equipment are effective for training in endoscopic surgical skills [1–3]. These training methods can also be used for evaluating endoscopic surgical skills [4] based on the movements of forceps, such as flight path, velocity, and accuracy. However, despite current advances in these objective assessments of endoscopic surgical skills, no functional brain studies during learning of endoscopic surgical skills have been carried out.

Motor learning is essential for acquiring motor skills, including endoscopic surgical skills. In general, two forms of motor learning can be distinguished, namely explicit and implicit learning [5]. Explicit learning involves conscious recollection of previous experiences, while implicit learning is defined as an unintentional nonconscious form of learning characterized by behavioral improvement. Motor skills progress from explicit control in the early stages of learning to more implicit or automatic control after thorough learning. Halsband et al. [5] suggested that motor learning consists of three distinct phases, designated the initial, intermediate, and

advanced phases. Although positron emission tomography [6] and functional magnetic resonance imaging [7, 8] have provided insights into the neuronal mechanisms underlying the learning and acquisition of motor skills based on analyses of finger or foot movements in the supine position, these functional imaging techniques are not suitable for evaluating cortical activation in subjects in the standing position. Therefore, there are no reports regarding cortical activation during motor learning of endoscopic surgical skills.

Recently, near-infrared spectroscopy (NIRS) has been developed to measure cortical activation during dynamic movements such as walking and running [9, 10]. NIRS can detect changes in the concentrations of cerebral blood hemoglobin (Hb), including oxy-hemoglobin (oxy-Hb), deoxy-hemoglobin (deoxy-Hb) and total hemoglobin (total-Hb), which reflect cortical activation. In the present study, we used multichannel NIRS to investigate cortical activation during endoscopic surgical tasks to elucidate the involvement of brain activation in the acquisition of endoscopic surgical skills, and possibly lead to the development of more efficient training systems.

### Methods

#### Subjects

A total of 21 healthy right-handed subjects participated in the present study. Thirteen of the 21 subjects were surgical novices at Kyushu University, among whom 6 had minimal experience of endoscopic training (one time; less than 2 h) and 7 had no experience. The other eight subjects consisted of four experts in endoscopic surgery with more than 2 years of experience as trainers at an endoscopic training center and four surgical trainees who had undergone endoscopic training once per month for 1–2 years.

#### Endoscopic surgical tasks

Suturing and knot-tying tasks were performed in a standard closed box endoscopic trainer (K26348; Storz, Tuttlingen, Germany) with a standard 20-inch and 60-Hz cathode-ray tube (CRT) display (Sony, Tokyo, Japan). Knots were tied as previously reported [11]. All the novices watched a video demonstrating the suturing and knot-tying procedures just before performing the tasks. The task periods were 60 s with rest periods of 20 s before the tasks and 30 s after the tasks.

#### Functional NIRS (fNIRS)

Cortical activation was assessed in all subjects by task-related changes in Hb oxygenation using an fNIRS system

(OMN-2001; Shimadzu, Kyoto, Japan), which consisted of seven near-infrared light (780, 805, and 830 nm) source fibers and eight detectors, resulting in 22 source–detector pairs (channels 1–22) and detected cortical changes in oxy-Hb, deoxy-Hb, and total-Hb after setting the interoptode distance to 3.0 cm. The optodes were fixed to the skull using a custom-made cap, and covered an area of  $13 \times 15$  cm over the front parietal cortices. Cortical activation was assessed as task-related increases in the oxy-Hb levels (mM-cm) since the changes in the deoxy-Hb levels were very small during both the task and rest periods under our experimental settings.

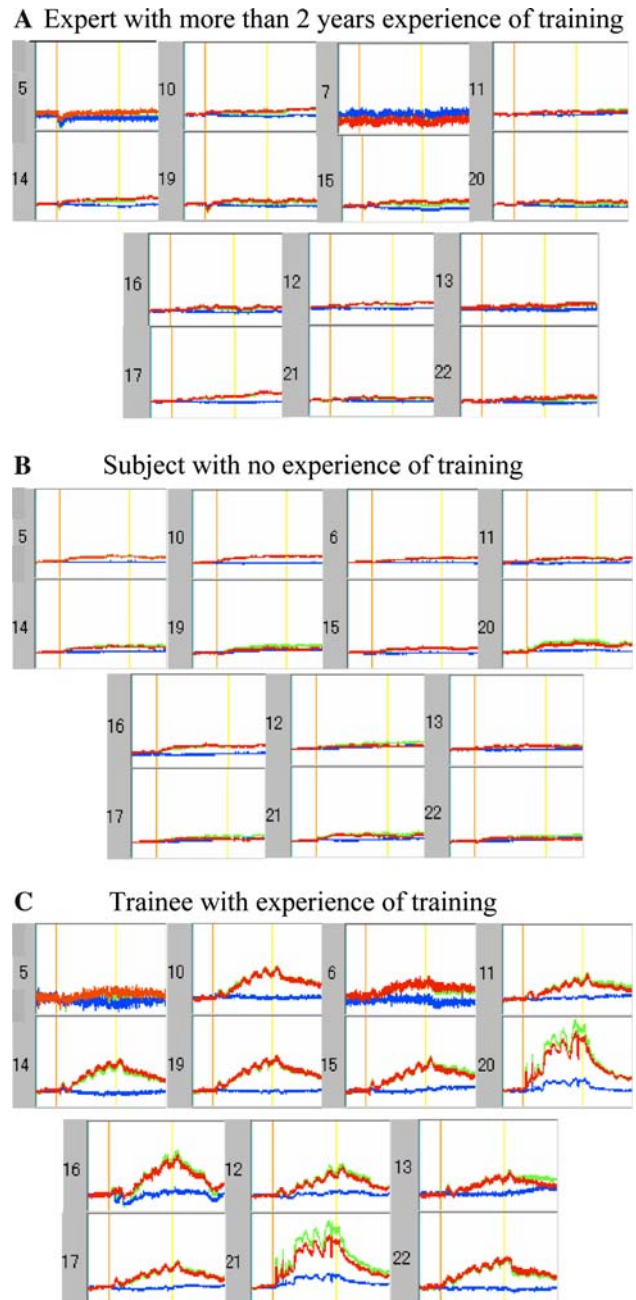
### Statistical analyses

Data were analyzed by the Mann–Whitney *U*-test because normal distributions were not obtained. Statistical significance was defined as  $p < 0.05$ .

### Results

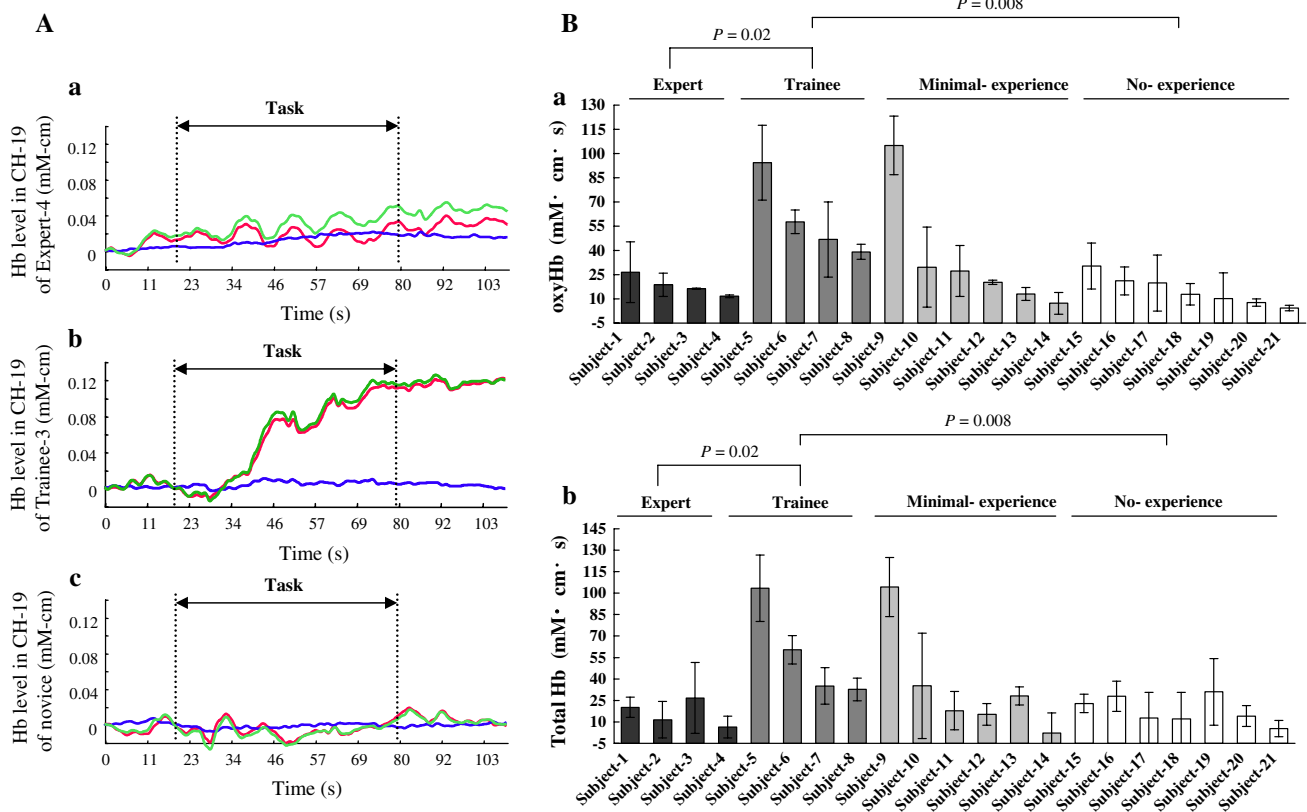
All four surgical experts completed a suturing procedure and repeated knot-tying tasks more than ten times during a limited period. All four surgical trainees completed a suturing procedure and repeated knot-tying tasks more than four times. All 13 surgical novices with minimal or no experience of training for endoscopic procedures performed knot-tying tasks fewer than three times.

In the analyses of surgical experts and surgical novices with no experience of endoscopic surgery training, we found no changes in oxy-Hb, deoxy-Hb or total-Hb levels in all frontal channels during the task and rest periods (Fig. 1A, B). On the other hand, in the analyses of surgical trainees and one surgical novice with experience of endoscopic surgery training, we found significant increases in oxy-Hb and total-Hb levels in most of the frontal channels during the task and subsequent rest periods (Fig. 1C). In particular, we found remarkable differences in oxy-Hb and total-Hb levels in CH-19 between surgical trainees (Fig. 2A–b) and surgical experts (Fig. 2A–a) or surgical novices with no experience of endoscopic surgery training (Fig. 2A–c). We statistically analyzed the data in CH-19, CH-22, CH-18, CH-17, CH-15, and CH-10. As shown in Fig. 2B–a and -b, there were significant differences in oxy-Hb and total-Hb levels in CH-19 between surgical experts and trainees ( $p = 0.02$  for both oxy-Hb and total-Hb) and between surgical trainees and surgical novices with no experience of endoscopic surgery training ( $p = 0.008$  for both oxy-Hb and total-Hb). We also found that there were significant differences in oxy-Hb levels in CH-22 ( $p = 0.02$ ) and CH-18 ( $p = 0.02$ ) between surgical experts and trainees and in CH-22 ( $p = 0.007$ ), CH-18



**Fig. 1** Representative data for task-related changes in oxy-Hb (red), deoxy-Hb (blue) and total-Hb (green) in frontal channels during laparoscopic surgical skill tasks. In the analyses of surgical experts (A) and surgical novices with no experience of endoscopic surgery training (B), no changes in oxy-Hb, deoxy-Hb or total-Hb levels were observed in any of the channels examined during the task and rest periods. In the analyses of surgical trainees (C), significant increases in oxy-Hb and total-Hb levels were observed in most of the channels during the task and subsequent rest periods

( $p = 0.007$ ), CH-17 ( $p = 0.014$ ), and CH-15 ( $p = 0.027$ ) between surgical trainees and surgical novices with no experience of training. On the other hand, we found no significant differences in CH-10 between all groups. Most of the surgical novices with minimal experience of



**Fig. 2** (A) Representative data in CH-19 for task-related changes in oxy-Hb (red), deoxy-Hb (blue) and total-Hb (green) during endoscopic surgical skill tasks. There are remarkable differences in oxy-Hb and total-Hb levels in CH-19 between surgical trainees (b) and surgical experts (a) or surgical novices with no experience of endoscopic surgery training (c). (B) There are significant differences

in oxy-Hb and total-Hb levels in CH-19 between surgical experts and trainees [ $p = 0.02$  for both oxy-Hb (a) and total-Hb (b)] and between surgical trainees and surgical novices with no experience of endoscopic surgery training [ $p = 0.008$  for both oxy-Hb (a) and total-Hb (b)]. Values are mean  $\pm$  standard deviation

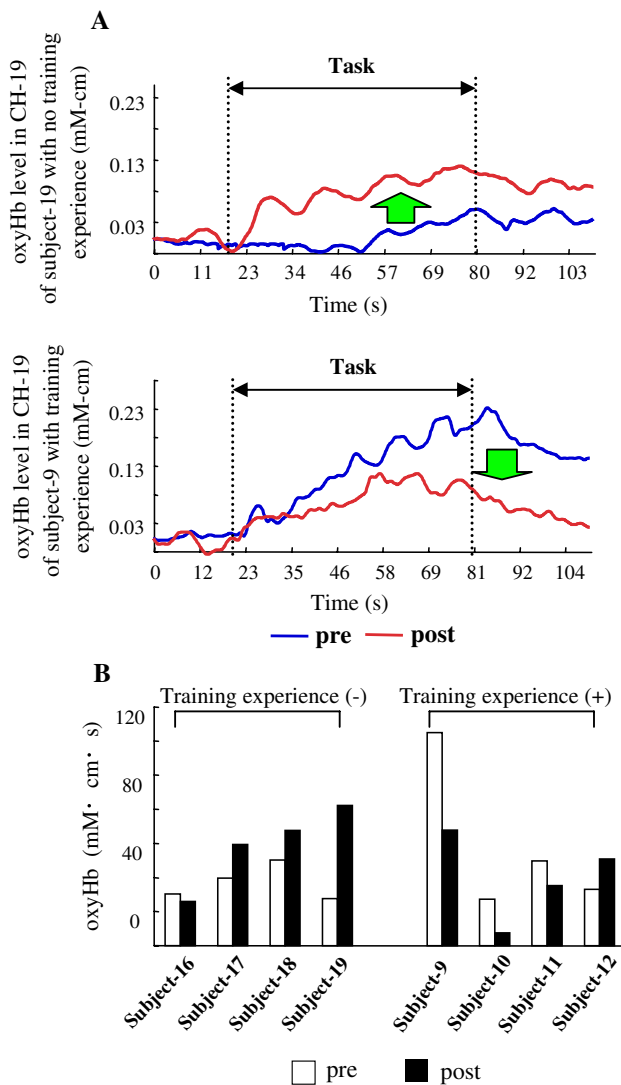
endoscopic surgery training also exhibited no significant changes in Hb levels in all channels observed, although we found remarkable increases in oxy-Hb and total-Hb levels in one surgical novice with minimal experience of endoscopic surgery training.

After initial assessment using the NIRS system, four surgical novices with no experience of endoscopic surgery training and four subjects with minimum experience of training were trained in suturing and knot-tying under endoscopic conditions for a single 2-h session, and then assessed again using the NIRS system. In three of the four subjects with no experience of previous training, oxy-Hb levels during the task and subsequent rest periods were remarkably increased after training compared with those before training (Fig. 3A and B). In three of the four subjects with minimum experiences of training, oxy-Hb levels during the task and subsequent rest periods were decreased after training compared with those before training (Fig. 3A and B). Especially, in subject 9, the oxy-Hb level was basically high before training session, but remarkably decreased after training session. We also investigated the

effect of additional practice on the brain activation of three surgical experts. Similar to the initial assessment before the additional practice, we found no frontal cortex activation in these surgical experts (data not shown).

## Discussion

This is the first report regarding brain activation during endoscopic surgery. Globally increased levels of oxy-Hb and total-Hb were only found in the frontal cortex of subjects who had experience of endoscopic surgery training, such as surgical trainees and surgical novices with minimal experience of training. We did not observe any changes in Hb levels in the frontal cortex of surgical experts and novices with no experience of endoscopic surgery training. We further found that additional training changed the oxy-Hb levels in the frontal cortex of surgical novices with no experience of endoscopic surgery training and subjects with minimum experience of training but had no such effect on surgical experts.



**Fig. 3** After an initial assessment, four surgical novices with no experience of endoscopic surgery training and four subjects with minimum experience of training were trained for a single 2-h session, and then assessed again using the NIRS system. (A) Representative data before (blue) and after (red) training. (B) In three of the four subjects with no experience of training, oxy-Hb levels during the task and subsequent rest periods are remarkably increased after training compared with those before training. In three of the four subjects with minimum experiences of training, oxy-Hb levels were decreased after training compared with those before training

It has been proposed that motor learning consists of three or two distinct phases, designated the initial, intermediate, and advanced phases [5] or the early and late phases [12–14]. Atkeson et al. [15] reported that movements are unskilled, highly feedback dependent, and require strong demands on attention during the early phase of motor learning. Activation of prefrontal areas is commonly reported to be involved in the sensorimotor association [16] and working memory [17] during the initial stages of explicit motor learning. Hatakenaka et al. [18]

also demonstrated that task-related increases in oxy-Hb levels in frontal regions actively change with acquisition of motor skills. In the present study, we also observed activation of the frontal cortex in subjects with experience of endoscopic surgery training, such as surgical trainees. After transient training, we also observed activation of the frontal cortex in surgical novices without previous experience of endoscopic surgery training. These findings suggest that the present subjects with experience of endoscopic surgery training were in the early phase of motor learning. It has been reported that, at the advanced stage of learning after long-term practice, movements become automatic and can be performed with high speed and accuracy, even if subjects do not pay attention to the actions [5]. In the present study, we did not observe any frontal cortex activation in the surgical experts during suturing and knot-tying tasks, suggesting that these surgical experts are at the advanced stage of motor learning. Taken together, the present data suggest that the NIRS system may be useful for assessing the stage of motor learning in individual subjects who have undergone training to acquire endoscopic surgical skills.

The first step toward increasing the level of patient safety in endoscopic surgery is for all endoscopic surgeons to acquire fundamental skills, including psychomotor skills. Box trainers and virtual-reality simulators have been well recognized as general training methods for endoscopic surgery and reported to be both instructionally effective and valid in their evaluation of surgical skills [4, 19]. In fact, both box trainers and virtual-reality simulators have frequently been reported to be useful for the acquisition of endoscopic surgical skills [20–25]. The large number of such reports suggests that the development of teaching, training, and assessment methods for endoscopic surgical skills is urgently needed to improve the safety of endoscopic surgery. The present study represents the first investigation of brain activation during endoscopic surgery using the NIRS system and reveals that activation of the frontal cortex is involved in learning of endoscopic surgical skills, especially during the initial phase of motor learning. Although our present study was preliminary, the results suggest that NIRS is a feasible tool for assessing brain activation during endoscopic surgical tasks, and may also provide important insights into the future development of teaching, training, and assessment methods for endoscopic surgical skills.

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