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Intraocular pressure increases after complex simulated surgical procedures in residents: an experimental study

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Abstract

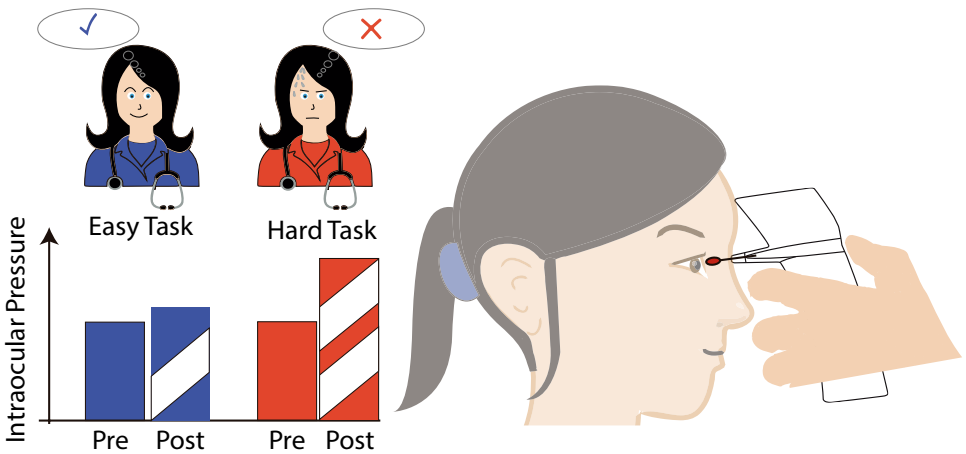
Background Surgeons' overload is one of the main causes of medical errors that might compromise patient safety. Due to the drawbacks of current options to monitor surgeons' load, new, sensitive, and objective indices of task (over)load need to be considered and tested. In non-health-care scenarios, intraocular pressure (IOP) has been proved to be an unbiased physiological index, sensitive to task complexity (one of the main variables related to overload), and time on task. In the present study, we assessed the effects of demanding and complex simulated surgical procedures on surgical and medical residents' IOP.

Methods Thirty-four surgical and medical residents and healthcare professionals took part in this study (the experimental group, $N=17$, and the control group, $N=17$, were matched for sex and age). The experimental group performed two simulated bronchoscopy procedures that differ in their levels of complexity. The control group mimicked the same hand-eye movements and posture of the experimental group to help control for the potential effects of time on task and re-measurement on IOP. We measured IOP before and after each procedure, surgical performance during procedures, and perceived task complexity.

Results IOP increased as consequence of performing the most complex procedure only in the experimental group. Consistently, residents performed worse and reported higher perceived task complexity for the more complex procedure.

Conclusions Our data show, for the first time, that IOP is sensitive to residents' task load, and it could be used as a new index to easily and rapidly assess task (over)load in healthcare scenarios. An arousal-based explanation is given to describe IOP variations due to task complexity.

Graphical Abstract



Keywords Cognitive load · Mental workload · Patient safety · Neuroergonomics · Ocular biomarkers

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Patient safety has become one of the main priorities of any healthcare system [1]. In the last years, the improvement of

medical training protocols, the advances in surgical techniques, and the increasing investment in other contributing factors that might decrease vulnerabilities (e.g., quality of infrastructures, efficiency of operational systems) have allowed a significant reduction of medical errors and incidents [2]. Yet, medical errors are a major cause of adverse events suffered by patients undergoing surgery procedures [1], with surgeons' overload as one of the main causes of these medical errors [3]. In the surgical context, increased task load imposed to the surgeon due to, for example, new demanding and complex surgical procedures [4] would lead to reduced levels of performance and increased likelihood of frustration [5]. Therefore, it is crucial to know when surgical demands, and the subsequent surgeons' overload, can compromise patient safety. The monitoring of surgeons to identify load variations is a challenge, and easy, rapid, and objective assessment tools are needed [6].

Traditionally, the primary and most disseminated assessment tools to monitor task load variations are based on subjective tests and questionnaires [7, 8]. However, self-reported measures present serious methodological limitations, as their dependence on personal and motivational factors that might jeopardize reliability (e.g., social desirability bias, halo and leniency effects, non-conscious activation) [9], or insufficient sensitivity to capture small load variations [10, 11]. Therefore, there is a growing interest to find sensitive and objective indices of surgeons' task load, which would be particularly relevant to patient safety [3]. Oculomotor indices have already proven to be effective for this purpose [4, 12]. For example, ocular indices such as eye blinks, pupil responses, and gaze dynamics have been previously used to capture task load variations among surgeons [3, 13–15]. Interestingly, intraocular pressure (IOP; i.e., the pressure exerted by the fluids of the eye against the outer coats of the eyeball) is sensitive to a wide range of physiological changes related to ocular functions (e.g., pupil size, axial eye length, anterior chamber depth) [16]. Furthermore, because the ocular system is tightly linked to the autonomic and central nervous systems [17], it is plausible to hypothesize that task load might also modulate IOP through an arousal-dependent process [18]. Recently, in non-surgical scenarios, researchers have found that IOP is sensitive to psychological and physical stressors (e.g., complex arithmetic tasks and strength training) or to induced fatigue (e.g., long monotonous driving) [18–21]. Considering that IOP is not under voluntary control [19] and it can be easily and rapidly assessed by rebound tonometry (see inset Fig. 1), IOP might represent a truly innovative index to assess task load variations among surgeons and other health care professionals.

Here, for the first time, we assessed the effect of two simulated bronchoscopy procedures, which differ in task complexity, on IOP in surgical and medical residents. We hypothesized that higher task complexity would lead to higher IOP values, independently of the time on task. We also expected that task complexity would be associated with reduced surgical task performance and increased levels of perceived task load.

Materials and methods

Ethical approval

We carried out the study in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and we obtained permission from the University of Granada Institutional Review Board (IRB approval #899). All participants signed a written inform consent before starting the study, and they received a compensation of 30 € for completing the experiment.

Participants

The participants were 34 members of the Andalusian healthcare system, naive to the aim of the experiment. To the best of our knowledge, this study is the first of its nature. Therefore, there was not applicable pilot data to calculate sample size a priori. To exceed the general convention of 80% power at the 5% level needed to conclude that a difference is significant for the main analyzed variable (i.e., IOP) between the 2 groups and the 2 procedures, and assuming an effect size of 0.30, a minimum sample size of 30 was required (15 participants per group) [22]. Seventeen surgical and medical residents (henceforth, residents) comprised the experimental group. Participants had received postgraduate training for an average of ~2 years (min 1 year, max 3 years). Fifteen residents (93.8%) had about 1 year or less of bronchoscopy experience. The other two had 1–3 years of bronchoscopy experience (6.2%). Residency specialties included anesthesiology (6), general surgery (4), critical care (4), and obstetrics-gynecology (3). To control for time on task [23] and the re-measurement effects [24], a control group of seventeen health care professionals, matched in sex and age with the experimental group, was also assessed. All participants had no history of ocular diseases, and normal or corrected-to-normal vision (two participants wore soft contact lenses, but wearing contact lenses does not affect IOP measurement [25]). For screening purposes, participants indicated their subjective levels of alertness before starting the experiment using the Stanford Sleepiness Scale (SSS) [26] (see the "Subjective questionnaires" section). Participants who scored more than 3 [27] were excluded from further analysis ($n=2$, one from the experimental group [a critical care medical resident] and another one from the control group). Thus, we finally analyzed data from 32 participants

(experimental group: 4 males, 28.31 ± 4.4 years old; control group: 4 males, 29.13 ± 4.08 years old).

Experimental design

The study followed a (2) × 2 × 2 mixed factorial design. We considered the *Group* (experimental vs. control) as the between-subjects factor, and *Task complexity* (Low complexity vs. High complexity, see "Surgical procedures" section) and *Measuring session* (pre-procedure vs. post-procedure) as the within-subjects factors. The dependent variables were IOP, perceived task load, and surgical performance (see "Performance data" section). The two groups (experimental and control) completed the same experiment within the same time (see "Surgical procedures" section). The only difference was that we encouraged only the experimental group to perform as accurately as possible the two procedures. Thus, the control group mimicked the same hand-eye movements and the posture of the experimental group, without suffering any intrinsic (i.e., task complexity) or extraneous (i.e., time pressure) load related to the surgical procedures. Both load categories, as well as movements and posture, can critically affect individual's physiological responses and, consequently, IOP [28, 29]. Thus, the main element that differs both groups was the task complexity experienced during the execution of the simulations. Finally, to minimize the potential effects of confounding factors as practice and learning effects, and task-switching costs (i.e., the costs associated with going from a complex task to an easy one), we implemented a Latin square design.

Instruments and measures

Surgical procedures

All participants performed the procedures on the AccuTouch® Endoscopy virtual reality simulator (Endoscopy AccuTouch® System, Immersion Medical Inc., Gaithersburg, MD, USA) [30]. The system provides visual, physical, physiological, and tactile feedback. Furthermore, the (simulated) patient exhibits signs that normally occur during surgical procedures (e.g., involuntary muscle contractions, vital sign changes, etc.). During the virtual simulation, performance-related data (e.g., the number of scope collisions with the airway walls) can be recorded [31].

In our study, participants performed two simulated bronchoscopic procedures, that differ in task complexity (Procedure A: low complexity and Procedure B: high complexity) as they present different levels of technical uncertainty [32, 33]. Briefly, during the *Procedure A*, participants had to intubate a 5-year-old child burned in a house fire 5 months earlier with a fiberoptic bronchoscope. It represents a low complexity procedure as the intubation process is a common and well-known procedure in bronchoscopy. During the *Procedure B*, participants had to perform a flexible bronchoscopy to identify the location of any visible lesion of a 42 years old female patient who presents with several episodes of blood-streaked sputum. It represents a high complex task due to the ambiguity induced by the identification of the problem [34] (see Appendix for a full description of both procedures). The mean time spent by the experimental group to complete each of the procedures (M ± SD [range]: 157.06 ± 37.79 [104–221] seconds, for the *Procedure A*, and 269.88 ± 149.70 [118–586] seconds for the *Procedure B*) was used to establish the maximum allowed time for the control group to complete the same procedures.

Intraocular pressure

A board certified optometrist (J.V.) performed the IOP measurements, using a clinically validated [35] rebound tonometry (Icare TA01, Tiolat Oy, INC. Helsinki, Finland). We measured IOP in both eyes [36], just before and after each of the two surgical procedures. Participants were instructed to fixate on a distant target while the probe of the tonometer was held at a distance of 4–8 mm, and perpendicular to the central cornea (see inset Fig. 1). Six rapid, consecutive measurements were taken in each eye (see Ref [35]. for more details). The Icare software discarded the highest and the lowest measures, and the mean IOP is calculated from the remaining four IOP values. To ensure the physiological validity of the recorded data, we calculated the intraclass correlation coefficient for both eyes (for each participant and for each of the four [two pre-procedure and two post-procedure] IOP measurements). All intraclass correlation coefficients were close to 1 (ranging from 0.948 to 0.989). Therefore, we considered the mean IOP value between eyes for further analysis [37]. Finally, to reduce both risks of missing any IOP changes and of having any cumulative effect due to the elapsed time, all post-procedure IOP measurements happened within 10 s after finishing the surgical procedures [21] and the interval between surgical procedures was ~ 5 min [19].

Subjective questionnaires

For screening purposes, we asked participants to fill in the SSS prior to starting the experimental session. The SSS is a 7-point Likert scale used to assess the self-reported level of activation, ranging from 1 "very active, alert or awake" to 7 "very sleepy" [38]. We also used the NASA Task Load Index (NASA-TLX) [39, 40] to assess the perceived task complexity at the end of each procedure. The NASA-TLX is composed of six subscales (mental, physical, and temporal demand, performance, effort, and frustration) and the scores

range from 0 to 100, with higher values indicating higher perceived task complexity.

Performance data

To assess participants' performance during the surgical procedures, we considered the execution time, the time in red-out (i.e., time during which airway anatomy cannot be visualized because of improper positioning of the bronchoscope) [41], and the number of scopes collisions with airway walls [42].

Procedure

We recruited the participants while they attended the Advanced Multifunctional Centre for Simulation and Technological Innovation (CMAT) at IAVANTE (Andalusian Public Foundation for Progress and Health), in Granada (Spain), for surgical training. Participants were instructed about the experiment, and, after signing the consent form, they filled the SSS and a demographic questionnaire. Then, when participants were in front of the simulator, we measured IOP. An instructions screen indicating the task to be performed preceded both procedures, and all participants were allowed with time enough to carefully read the case history and objectives of each surgical procedure. For the control group, we explained them that it was not necessary to follow any specific procedure. After reading the instructions, the participants started the first surgical procedure. When they finished, we immediately measured IOP at the same standing position and we administered the NASA-TLX. This sequence was repeated for the second surgical procedure. Participants were not allowed to rest between procedures, with the exception of IOP and NASA-TLX assessments. The entire session lasted ~ 40 min.

Statistical analysis

To analyze the subjective ratings of perceived complexity (NASA-TLX scores), and surgical performance (execution time, time in red-out, and number of scopes collisions), we performed four paired samples *t* tests only for the experimental group, considering the task complexity (low vs. high) as the within-subjects factor. To ensure that both groups were similar in terms of their baseline IOP at the beginning of the experiment, we performed a *t*-test for independent samples (i.e., groups) comparing the IOP measurements before starting the first surgical procedure. Finally, to analyze the effect of *Task complexity* on IOP, we implemented a $(2) \times 2 \times 2$ mixed factorial ANOVA, with *Group* (experimental vs. control) as the between-subjects factor, and *Task complexity* (low vs. high) and *Measuring session* (pre-procedure vs. post-procedure) as the within-subjects factors. The assumptions of normality of both IOP data and residuals (Shapiro–Wilk test and a graphical assessment), independence (residual plot), and homoscedasticity (Levene's test) were always confirmed. We reported Cohen's *d* and partial eta-squared (η_p^2) as effect size indices. We used Holm–Bonferroni corrections for multiple comparisons. The level of significance was set at 0.05.

Results

Effectiveness of the task complexity manipulation: perceived task complexity and performance

Participants reported higher perceived task complexity (as expressed by the NASA-TLX scores) for the *Procedure B than* for the *Procedure A,* $t(15) = -2.87$, $p = 0.012$, $d = 0.82$ (see Table 1). In general, surgical performance confirmed the subjective ratings of complexity. The execution time, $t(15) = -2.88$, $p = 0.029$, $d = 1.20$, and the time in red-out, $t(15) = -2.62$, $p = 0.029$, $d = 1.22$, were longer for the high complexity task. Although the number of scopes collisions did not differ, $t(15) = -0.55$, $p = 0.59$, they were also larger (see Table 1). All together, these results indicate a successful task complexity manipulation, being the *Procedure B* more demanding than the *Procedure A*.

Effects of surgical task complexity on intraocular pressure

There were no significant differences between groups in baseline IOP measures, $t(15) = -0.80$, $p = 0.43$, confirming that the matching procedure worked properly.

Table 1 The effects of *Task* complexity on the NASA-Task Load Index (NASA-TLX) scores, the execution time, the time in red-out, and the number of scopes collisions in the experimental group ($N = 16$)

	Procedure A Low complexity M ± SD	Procedure B High complexity M ± SD	*p* value
NASA-TLX scores	43.07 ± 16.9	58.18 ± 19.86	0.012
Execution time (s)	157.07 ± 37.79	269.88 ± 149.7	0.011
Time in red-out (s)	12.5 ± 5.38	39.56 ± 39.03	0.019
Number of scopes collisions	15.56 ± 25.28	21.44 ± 30.29	0.592

NASA-TLX scores range from 0 to 100, with higher values indicating higher perceived task complexity. Surgical performance values are reported in seconds for execution time and time in red-out, and scopes collisions represent the number of times that this occurred. In all cases, higher values indicate poorer performance

M mean, *SD* standard deviation

The mixed factorial ANOVA yielded significant main effects for *Task,* $F(1, 30) = 9.28$, $p = 0.004$, $\eta_p^2 = 0.24$, and *Measuring session,* $F(1, 30) = 31.89$, $p < 0.001$, $\eta_p^2 = 0.52$. The *Group* did not reach statistical significance ($F < 1$). The interaction *group* × *measuring session* was significant, $F(1, 30) = 30.39$, $p < 0.001$, $\eta_p^2 = 0.50$. Besides, there was a significant second order interaction between *group* × *task complexity* × *measuring session,* $F(1, 30) = 6.36$, $p = 0.017$, $\eta_p^2 = 0.18$. IOP increased as consequence of performing the most complex task (*Procedure B*) only in the experimental group (corrected *p*-values < 0.05). For the control group, IOP was stable across all the procedures and measuring sessions (corrected *p*-values > 0.05) (see Fig. 1; Table 2).

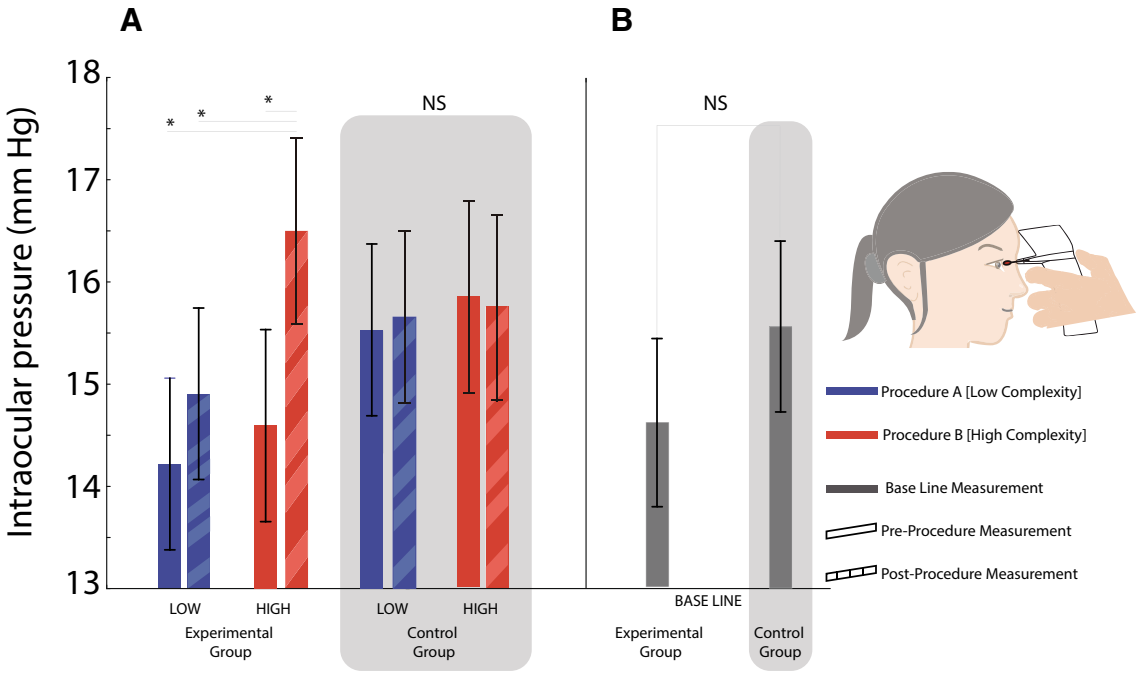

Fig. 1 Effects of *Task complexity* on intraocular pressure (IOP) measured with a rebound tonometer in the experimental ($N = 16$) and the control ($N = 16$) groups. **A** Average intraocular pressure before and after performing each procedure for both groups. Data from the low complexity task (*Procedure A*) are displayed in blue, and from the high complexity task (*Procedure B*) in red. **B** Baseline IOP values for both groups. The shadow areas represent data from the control group. Error bars represent the standard error of the mean. *NS* non-significant differences. *Corrected *p*-values < 0.05. (Color figure online)

Table 2 The effects of *Task* complexity on intraocular pressure (IOP, in mmHg) in the experimental ($N = 16$) and the control ($N = 16$) groups for the baseline measurements (taken right before starting the experiment), and before and after each exercise

	First measuring session	Procedure A Low complexity		Procedure B High complexity	
	Baseline†	Pre-procedure	Post-procedure	Pre-procedure	Post-procedure
	M ± SD				
Experimental group	14.62 ± 3.29	14.22 ± 3.53	14.91 ± 3.24	14.59 ± 3.8	16.5 ± 3.65*
Control group‡	15.56 ± 3.35	15.53 ± 3.18	15.66 ± 3.46	15.84 ± 3.71	15.75 ± 3.62

The mean and standard deviation of IOP were calculated from both eyes

IOP intraocular pressure, *M* mean, *SD* standard deviation

*IOP increased as consequence of performing the most complex task (procedure B) only in the experimental group (corrected *p*-values < 0.05)

‡IOP was stable across both procedures (A and B) and measuring times (pre and post) in the control group (corrected *p*-values > 0.05)

†Non-significant differences between groups in baseline IOP measures, $p = 0.430$

Discussion

We examined the effects of surgical task complexity on IOP, bronchoscopic performance, and perceived task complexity in surgical and medical residents. Our results show that task complexity modulates residents' IOP during simulated standardized bronchoscopic procedures: IOP increased with higher task complexity (i.e., more challenging procedures) (Fig. 1). To the best of our knowledge, no previous studies had examined the effects of task complexity on IOP in surgical scenarios. However, these findings are in accordance with similar studies in non-health care scenarios that showed that IOP is sensitive to cognitive state variations, as those induced by low and high operator's arousal levels (fatigue [18] and stress [43]). A similar arousal-based effect might explain the IOP rise we found here, after the residents performed a more demanding and complex surgical procedure. Thus, because task complexity modulates arousal [44], it might explain the IOP rise. The association between arousal's level and IOP might be explained by the fact that the autonomic nervous system regulates IOP (i.e., the balance between the aqueous humour inflow and outflow) with a crucial role of the sympathetic-adrenal branch [16]. In this line, our manipulation supports a bidirectional relationship between IOP and the nervous system's activation state [43]. Therefore, fluctuations in the nervous system's activation state will cause IOP changes, as it has also been corroborated by the cardiovascular response analysis [19].

The current study presents evidence on the utility of IOP as an index of task load during residency surgical training. IOP seems to be a good candidate to assess task (over)load, as other ocular indices such as the ocular dynamics [45, 46] or the pupil size [17, 47]. IOP assessment presents numerous advantages over these other indices, which are especially relevant in applied settings: IOP is a rapid, simple to obtain, easy to analyze, and a well-tolerated procedure [35]. Furthermore, a recent development of contact-lens sensors (e.g., SENSIMED Triggerfish, Lausanne, Switzerland; see Mansouri et al. for more details [48]) allow to easily and comfortably continuous monitoring of IOP [49]. Thus, technological advances would help to reveal novel insights about surgeons' cognitive state into real operating rooms [49]. Continuous IOP monitoring before, during, and after the procedures would also allow to obtain relevant data for understanding the IOP behavior during mentally demanding tasks. Moreover, the use of an IOP-based index could be of relevance in surgical training programs in order to evaluate the level of task (over)load imposed to surgical trainees, and it might permit to adjust to reach a desirable task complexity. Thus, monitoring IOP variations could lead, in the near future, to a workload surgeon's fit-for-duty system, integrated into wearable devices, with a similar reasoning as the operator's fatigue detectors. Those detectors are based on eyelid behavior and permit to objectively assess the level of fatigue and drowsiness (e.g., Optalert, Cremorne, Australia, see [50] for more details).

There are some aspects that might limit the impact of the present findings in healthcare scenarios. First, in the context of assessing day-to-day training duties, we allowed residents to continue their schedules and routines. Thus, we did not give any particular instructions about to caffeine (or other stimulants) consumption. Even though participants were not allowed to drink (or eat) during the course of the experiment, hydration status or previous caffeine consumption might have influenced their IOP response [51, 52]. Second, we measured IOP in a pre/post manner while residents were performing short simulated surgical procedures. Future studies should investigate the effect of longer tasks and working sessions on IOP, as well as the possible effects of accumulated workload [19]. Considering that healthcare professionals comply with extended working hours, which causes fatigue among residents [53] and might impair performance [10, 54], those studies would have a significant impact on patient safety strategies and residency training programs. Interestingly, a recent study from our laboratory [18] found that IOP is sensitive to detect driver fatigue after a long experimental session (~2 h). Finally, one may wonder if differences among residents in their psychomotor skills (e.g., eye-hand coordination) [55] or medical specialty [56], as well as in expertise in a particular procedure [57], might have affected the present changes in IOP. This possibility seems unlikely in light of the implemented experimental design, as well as the inclusion of a control group.

Conclusions

Our results showed that IOP increased with higher complexity of the surgical simulated procedures, suggesting an association between the nervous system's activation state and the IOP behavior. The current results might have potential impact for the development of a future valid, sensitive, easy, rapid, and well-tolerated neuroergonomic tool to evaluate task load during surgical training and procedures (real and simulated), allowing to objectively assess the residents' capacity to operate at their optimum level of function. This approach should be followed by observational studies in real operating rooms to ensure the robustness and generalizability of our findings.

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Compliance with ethical standards

Disclosures Drs. Vera, Diaz-Piedra, Jiménez, Sanchez-Carrion, and Di Stasi have no conflicts of interest or financial ties to disclose.

Appendix

Before starting the procedure, participants read the following information:

For the *Procedure A*, A 5-year-old child scheduled for split thickness skin grafts (STSG). He was burned in a house fire 5 months ago and has 70% TBA burns. He has required multiple anesthetics for burn dressing changes and STSGs. His last anesthetic, 2 weeks ago, was discussed extensively in your department because the anesthesiologist had a very difficult time intubating the patient, due to a Grade 3 view with laryngoscopy. It is decided that the safest way to intubate this patient is with a fiberoptic bronchoscope.

On physical exam, the child has extensive burn scars and contractures. The scarring on his face and anterior neck severely restricts his ability to open his mount or extend his head.

For the *Procedure B*, A 42 years old female who presents with several episodes of blood-streaked sputum. She smoked for 10 years, but quit 5 years ago. On physical examination, she is afebrile and appears well. Her blood pressure is 110/75, pulse is 84, temperature is 98.4 F, and respiratory rate is 14. No abnormalities are noted on auscultation of the chest. No lymphadenopathy is present. Her chest radiographs are normal.

Please perform flexible bronchoscopy to identify the location of any lesions that you can visualize. Capture an image of each lesion identified by depressing the video capture button on the bronchoscope.

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