The Journal of Education in Perioperative Medicine

Original Research

The Use of a Hemodynamic Monitor Perceptual and Adaptive Learning Module to Improve Clinical Interpretation Skills in Anesthesiology Residents

Jason S. Lee, MD
Azad J. Hirpara, MD
Sally Krasne, PhD
Philip J. Kellman, PhD
John A. Kleinman, MD
Boss Le, MD, MPH
Bryan T. Romito, MD, MBA

Introduction

Effective training of the next generation of anesthesiologists requires a combination of teaching methodologies tailored to specific learning objectives.[1] Educational innovations, including modules and simulation training, augment traditional content delivery by providing immersive opportunities to practice essential skills. However, not all residency programs have access to novel resources and facilities.[2] As anesthesiology is often learned best by scaffolding classroom learning with clinical exposure, reflection, and simulation, there is a continual need for curriculum development that incorporates diverse, practical, effective approaches to education.

Perceptual learning refers to adaptations made through improved interpretation of sensory stimuli.[3] Pattern recognition and cognitive expertise are developed though perceptual learning mechanisms as sensory associations strengthen.[4] Perceptual and adaptive learning modules (PALMs) are educational tools that can display a series of classification trials (single-answer multiple-choice questions). To learners, the PALMs seem like electronic flashcard programs, but they include features designed to augment pattern recognition and enhance long-term memory.[5–9] They incorporate 2 main approaches:

1. To invoke and transfer perceptual learning to new presentations, items are assigned to their relevant categories (diagnoses), so when learners are presented with a new trial, a unique exemplar is presented.[9] Following answer selection, feedback on accuracy and the correct choice are provided.

2. To make learning efficient, category sequencing and spacing follow the Adaptive Response Time-based Sequencing protocol.[7,10] This system is a computer algorithm that uses learners' individual performance to adaptively sequence and space learning categories.[9] The protocol assigns a priority score to subsequent categories based on elapsed time or trials, response time, and accuracy. New examples from incorrectly classified categories appear sooner than those from correctly classified categories. Examples from correct but slowly classified categories appear sooner than correct and rapidly classified categories. Priority scores are updated after each trial to adjust to the learners' progress. A category is retired after a predetermined number of consecutive, correct classifications are made within a target time, representing "mastery."

Online PALMs have been created to enhance proficiency in pattern recognition–dependent domains across medical specialties.[5,11–14] Elements of pattern recognition are widespread in anesthesiology. Predicting difficult intubation,[15] performing ultrasound-guided regional and neuraxial anesthesia,[16,17] interpreting processed electroencephalography,[18,19] and monitoring/preventing clinical deterioration incorporate these principles.[20,21] We previously created a PALM that displayed cardiac abnormalities in transesophageal echocardiography (TEE) video loops and found that first-year anesthesiology residents exposed to our PALM significantly improved their accuracy and fluency in diagnosing cardiac pathology.[12]

Interpreting vital sign and waveform abnormalities are foundations of anesthetic practice. Although life-threatening events are associated with characteristic waveform abnormalities,[22–25] these may be difficult for novices to quickly recognize due to inexperience. We hypothesized that exposure to a hemodynamic monitor PALM would enhance learners' abilities to identify these changes. The current study examines the impact of an online hemodynamic monitor PALM on the accuracy and fluency in diagnosing clinical abnormalities in first-year anesthesiology residents compared with residents not using the PALM.

Materials and Methods

This was a prospective, randomized, controlled trial conducted within the

continued on next page

continued from previous page

Department of Anesthesiology and Perioperative Medicine at Ronald Reagan University of California Los Angeles Medical Center and the Department of Anesthesiology and Pain Management at the University of Texas Southwestern Medical Center. This study was exempted by the institutional review board at both institutions, and the requirement for written informed consent was waived as this was an educational study. The 2 sites chosen for the study were the home institutions for the study investigators. The individuals in the study were all first-year anesthesiology trainees who were members of the Categorical Anesthesiology Residency Program at both sites. All first-year anesthesiology trainees were contacted via email (by S.K. at University of California Los Angeles and B.T.R. at University of Texas Southwestern) to invite them to participate in the study and informed that their participation was voluntary and would have no impact on their residency training. All individuals who chose to participate were included in the study. No other eligibility criteria were defined. Individual characteristics of the participants were not collected. The study was conducted from March 2021 to July 2021 and an additional cohort in March 2022 to July 2022, extending over the month-long introductory anesthesiology rotation completed by each trainee in either the control or intervention group before beginning their clinical anesthesia years. The University of California Los Angeles first-year residents stagger their introductory anesthesiology rotation in the months of March through June, whereas those at the University of Texas Southwestern complete their introductory anesthesiology rotation together in June. All the training, tests, and PALM (for the PALM group) that were part of the study were incorporated into each institution's existing introductory rotation for their respective residents. The rotations include each institution's unique formal lectures on basic hemodynamics and management of common intraoperative problems, exposure to simulated patient care scenarios, and intraoperative clinical work supervised by anesthesiology attendings and senior residents.

A per-protocol analysis was undertaken as the study's primary goal was to evaluate the impact of the PALM at 1 month when used as intended and when added to the regular teaching that occurs during an introductory clinical anesthesia rotation in novices. For this reason, we excluded from the final analysis those residents who did not complete the PALM in its entirety, those residents in the control group who mistakenly completed parts of the PALM, and any residents who did not complete all the required tests.

Intervention

This study was initiated at the beginning of the residents' rotation, prior to the basic hemodynamic lectures that all first-year residents receive during their introductory anesthesiology rotation. Using simple randomization with computer-generated numbers via the website https://www.random.org, participants from each residency program were randomized in a 1:1 allocation ratio to 1 of 2 parallel groups: either the experimental group that utilized the PALM (PALM group) or the non-PALM control group. Randomization occurred when the residents agreed to participate in the study. At the start of their rotation, residents in each group completed a hemodynamic monitoring pretest followed by a brief tutorial training session and then an immediate posttest after the training session. The PALM group completed the PALM after their tutorial session, whereas the control group did not complete the PALM. At the end of their month-long rotation, the trainees were asked to complete a delayed test. All components of the training and assessments were completed by the residents at the location of their choosing through online modules sent out by email (by S.K). The residents were not monitored by any member of the study team while engaging with this online exercise. Residents were aware of their group assignment as those randomized to the PALM group completed the PALM, whereas those randomized to the control group did not. All other study personnel and clinical faculty involved in resident education were blinded to the allocation groups. Clinical faculty were not involved in the tutorial sessions. Clinical faculty involved in resident training did not receive extra instructions pertaining to this study. The curriculum for the introductory rotations was not altered based on this study.

Training for both the PALM and control groups began with a tutorial slide show consisting of a sequence of seven slides, each shown for 30 seconds and displaying a dynamic hemodynamic monitor tracing consistent with 1 of the 7 diagnoses to be learned. The slides were accompanied by text identifying the critical features associated with the diagnosis and some brief explanation of the physiology giving rise to these features. Displays included audio and visual alarms that mimic the operating room environment. The 7 diagnoses used in this study included normal, acute coronary syndrome, anaphylaxis, hypovolemia, malignant hyperthermia, pulmonary embolism, and ventricular tachycardia/fibrillation. The text for each slide is shown in Table 1. This tutorial was the extent of the training for the control group. For the PALM group, the tutorial was followed immediately by the PALM.

Hemodynamic Vital Sign Tracings

The vital signs in the hemodynamic monitor PALM displayed changes in heart rate, blood pressure, electrocardiogram (ECG) tracings (leads II and V1), temperature, pulse rate, oxygen saturation, and end-tidal carbon dioxide concentration. Video recordings of vital sign monitors were simulated using Laerdal LLEAP and B-Line Medical simulation software. A total of 198 such simulations were used in this study, 42 as stimuli for the assessments (2 per diagnosis per assessment version) and 156 (ranging from 19 to 25 for a given diagnostic category) as stimuli for the PALM. No 2 records were identical with each utilizing a different set of physiologic parameters consistent with the diagnosis. Each presentation was 30 seconds long, beginning with approximately 5 seconds of a normal vital sign loop and then changing to a set of parameters that produced a tracing, lasting approximately 15 seconds, characteristic of the desired diagnosis. The final frame was maintained for approximately 10 additional seconds

continued on next page

continued from previous page

to make the total viewing time 30 seconds for each record. The scenarios depicted in the tracings were the same for both institutions.

Hemodynamic Monitor PALM Metrics

For the hemodynamic monitor PALM, a minimum of 3 intervening trials were required before category repetition, and category retirement required 3 consecutive, accurate classifications within 20 seconds (the target response time). The target response time was based on feedback from 2 anesthesiology faculty members as well as on PALM testing by 4 senior anesthesiology residents. Those involved in this trial run were part of residency leadership at UCLA. These individuals had formal simulation training, and the target response time was determined by consensus. The target response time represents a threshold value for the speed of (accurate) recognition desired for the trainee group.

For each problem in the PALM, trainees were asked to classify the video tracing into 1 of 7 categories (diagnoses) described above and in Table 1. After selecting an answer choice, feedback was displayed. If no answer was chosen within 30 seconds, the response was counted as incorrect, and the display automatically moved to the feedback. Feedback consisted of the final view of the trace; an indication of whether the trainees' answer was correct or incorrect; if incorrect, an indication of the correct answer choice; and finally, a summary of the critical features that should have led the trainees to the correct diagnosis (extracted from the descriptions accompanying slides in the tutorial). If the answer choice was correct, the response time was also displayed. There was no time limit to how long the participants could view the feedback. After every block of 12 trials, a summary feedback slide was provided that summarized the participants' performance thus far.

Assessment

To assess the effectiveness of the PALM, tests were developed to measure the participants' ability to identify unseen videos of the 7 categories before the PALM (pretest), immediately after the PALM (immediate posttest), and 1 month later at the end of the anesthesiology rotation (delayed test). These assessments were created as straightforward computer-based, multiple-choice tests with no feedback (Figure 1). Problems were presented in random order with no enforced spacing or sequencing. Three different versions of assessments were developed for the tests, each consisting of 2 examples per category of vital sign tracings, each unique to the test as well as different from tracings used in the PALM. The 3 assessment versions were balanced within each of the test types with approximately a third of the group completing a given version of the assessment for each test. Each trainee also received a different version of the assessment for the pretest, immediate posttest, and delayed test. The pretest, immediate posttest, and delayed test provided the same functionality as what was displayed in the PALM.

Statistical Analysis

There was no a priori statistical power calculation for this study because there was no basis for determining the sample size needed to see a given effect size as prior studies in this domain had not been performed. Two separate primary outcomes at 1 month were analyzed: accuracy was calculated as the percentage of responses that were correct, and fluency was calculated as the percentage of responses that were both accurate and made within the target 20-second response time. All outcomes were decided a priori. Differences between pretest, immediate posttest, and delayed test performance within each group and among categories were assessed by correlated (paired), 2-tailed *t*-tests. Differences between groups were assessed by independent, 2-tailed *t*-tests. Statistical significance was accepted at a value <.05 for all secondary outcomes. We applied a Bonferroni correction for multiple comparisons for our primary outcomes, resulting in a Bonferroni-adjusted alpha of 0.025. Effect size (Cohen's *d*) was calculated as the difference in means divided by the pooled SD. Confidence intervals were also calculated. Statistical analyses were performed using VassarStats (http://vassarstats.net/).

Results

Of the 30 categorical trainees at the University of California Los Angeles, 29 were included in the study (1 chose not to participate). Of the 17 categorical trainees at the University of Texas Southwestern, 12 were included in the study (5 chose not to participate). Figure 2 shows the final flow diagram for the study. As shown, there was dropout of participants between the pretest and delayed test.

The total number of residents randomized was 41. Of these 41 randomized residents, 20 were randomized to the PALM group, and 21 were randomized to the control group. All 20 residents in the PALM group completed the pretest, and all 21 residents in the control group completed the pretest. Because of voluntary attrition and data exclusion, 17/20 residents in the PALM group completed the immediate posttest, and 16/21 residents in the control group completed the immediate posttest. Because of voluntary attrition, 10/16 residents in the control group who completed the immediate posttest went on to complete the delayed test. All 17/17 residents in the PALM group who completed the immediate posttest went on to complete the delayed test. Thus, the total number of residents who completed through the delayed test and were included in the final analysis was 17/20 in the PALM group and 10/21 in the control group. The total attrition/exclusion rate for the study was 34.1% (14/41). The control group had an attrition/exclusion rate of 52.4% (11/21), whereas the PALM group had an exclusion rate of 15.0% (3/20).

Residents were excluded from the study for several reasons. Three PALM group participants failed to complete the PALM. Two control group participants could not finish beyond the pretest stage due to technical difficulties. Three control group participants were excluded from analysis of the immediate posttest and delayed test because they mistakenly completed part of the PALM following the pretest. Finally, 6 control group participants simply failed to complete the delayed test before finishing the rotation.

PALM and control groups showed similar pretest performances. This analysis

continued on next page

continued from previous page

considered both participants who were only able to complete the immediate posttest as well as those who completed through to the delayed test. For the tutorial, both groups spent 3.5 minutes on the 7-slide teaching presentation. The PALM group spent an additional average of 15.9 (±6.9) minutes completing the PALM. Accuracy and fluency improved significantly from pretest to immediate posttest for both the PALM (accuracy, 63% ± 4% vs 89% ± 2%, $p < .0001$, $d = 2.5$; fluency, 36% ± 3% vs 74% ± 3%, $p < .0001$, $d = 3.0$) and control groups (accuracy, 59% ± 5% vs 80% ± 4%, $p < .0001$, $d = 1.2$; fluency, 33% ± 4% vs 62% ± 5%, $p < .0001$, $d = 1.7$) with large effect sizes (Figure 3).

By contrast, at the 1-month delayed test, performance for the PALM group remained statistically significantly better compared with pretest values for both accuracy (87% ± 3%, $p < .0001$, $d = 2.1$) and fluency (64% ± 4%, $p < .0001$, $d = 1.9$) with persistently large effect sizes, whereas the control group scores were not (accuracy, 67% ± 6%, $p = .13$, $d = 0.4$; fluency, 45% ± 6%, $p = .11$, $d = 0.7$). (Figure 3).

Figure 4 summarizes the between-group statistics for the PALM versus control groups on all tests. For the delayed tests (rightmost blue-to-yellow bar comparisons of Figure 4), the differences between the PALM and control groups were statistically significantly greater with large effect sizes (accuracy, 87% ± 3% vs 67% ± 6%, $p = .001$, $d = 1.39$; fluency, 64% ± 4% vs 45% ± 6%, $p = .01$, $d = 1.11$). By contrast, there were no statistically significant differences between the pretests for the PALM versus control groups for either those completing through the posttest or those completing through the delayed test.

Table 2 reports how many attempts were made, both total and per (PALM group) participant, for problems in each category prior to retiring the category during the PALM. Acute coronary syndrome, anaphylaxis, and hypovolemia required many more trials to master than the remaining categories.

Results of an analysis of sensitivity and specificity in category identification for PALM versus control groups are shown as a function of testing phase in Table 3. The overall values for sensitivity and specificity are also calculated along with the within-group statistics for performance on the posttest and delayed test relative to the pretest. Changes for the PALM group are statistically significant relative to the pretest, whereas those for the control group are significant only for the posttest relative to the pretest.

Discussion

Our results demonstrate that brief exposure to an online PALM significantly improved both accuracy and fluency in identifying several clinical abnormalities using hemodynamic monitor changes in a sample of first-year anesthesiology residents compared with residents not completing the PALM. Based on the effect sizes, performance of the PALM group improved by approximately 2 SD between the pretest and the delayed test, whereas the performance of the control group improved by approximately 0.4–0.7 SD during this period.

Residents in both groups displayed pretest performance that was sufficient to indicate some background understanding of the waveform changes associated with the diagnoses. The 3.5-minute tutorial with the slide presentation resulted in a statistically significant improvement in posttest accuracy and fluency of both the groups at 30 minutes compared with the pretest. However, in contrast to gains on the immediate posttest, the tutorial training combined with training that occurred over the course of the 1-month rotation did not provide significant prolonged learning gains for the control group as determined from their performance on the delayed test compared with the pretest. Conversely, the PALM, combined with training during the rotation, provided sustained learning gains as evidenced by statistically significant improvements in delayed test accuracy and fluency at 1 month relative to pretest values.

Not all diagnoses included in our study were identified with equal proficiency. We analyzed how many trials the 17 PALM participants required to retire each of the categories to determine which diagnoses were particularly easy for them to recognize and which were more difficult. Ventricular tachycardia/ventricular fibrillation, malignant hyperthermia, and normal were easily recognized. This observation is not surprising given the characteristic clues for the first 2 diagnoses (erratic ECG tracing and markedly elevated temperature and lack of change from initial behaviors, respectively). The sensitivity and specificity in identifying all diagnoses showed significant improvement between the pretest and posttest for both the PALM and control groups. This improvement was maintained after the month of clinical training on the delayed test only for the PALM group (Table 3).

The exact mechanism by which the PALM augmented the residents' learning is unknown. It has been suggested that pattern recognition skills produced by perceptual learning deteriorate more slowly than declarative learning[9] as in the common wisdom that one never forgets how to ride a bicycle, a task that depends heavily on perceptual motor skill learning. If so, the PALM group may differ from the control group not only in overall delayed test performance but also in maintaining stronger pattern recognition skills that are more characteristic of expert task performance. It is possible that the short-term perceptual learning gains achieved through the PALM were converted to long-term memory through a memory consolidation-reactivation process that occurred following subsequent exposure to similar material during their clinical rotation.[26,27] It is also possible that early exposure to the PALM enabled the residents in that group to extract more information from related experiences, a core principle of perceptual learning theory.[6]

Compared with traditional education methods that focus on passive learning via lecture presentations and textbook readings, the hemodynamic monitor PALM provides an alternative approach to accelerate the recognition, by novice providers, of waveform-based clinical deterioration. As an online, self-directed tool, the PALM allows learners to engage in the content on their own time and from any location with internet computer access. Whereas it does not replicate the hands-on experience of simulation

continued on next page

continued from previous page

training, the PALM does not require specialized equipment (beyond a computer or tablet), physical space, or additional personnel to enhance the experience, offering a novel educational option to training programs with limited simulation resources or low surgical volumes. The hemodynamic monitor PALM closely approximates a portion of the American Board of Anesthesiology Applied Examination that involves interpretation of vital sign abnormalities and changes. Integrating both PALMs and simulation-based training could offer a more comprehensive educational experience, combining the sustained cognitive skill development facilitated by PALMs with the tactile, auditory, and procedural feedback provided by simulation environments.

The present study expands on our previous work on a TEE PALM in several ways.[12] Whereas TEE has a prominent role in the management of cardiac surgical patients, it has limited utility in other settings and is not routinely used by general anesthesiology providers. Conversely, the data presented in the hemodynamic monitor PALM are ubiquitous in the operating room and critical care setting, and the 6 pathologies included in the present study represent common situations associated with perioperative cardiac arrest.[28] In this manner, the results of the current study are widely applicable. Whereas there is no direct evidence linking PALMs to enhanced situational awareness in life-threatening clinical scenarios specific to anesthesiology, the principles of PALMs—improving pattern recognition and adaptive learning—have been utilized in various fields of medical education (ECG, histopathology, dermatology, radiology interpretation, etc). By improving cognitive processes that will ultimately be utilized in the clinical setting, PALMs can indirectly support anesthesiologists in recognizing and responding to critical situations more effectively.

Our study is not without limitations. We did not collect background characteristics on the subjects; however, pretest performance was similar between the 2 groups. We only included 7 diagnoses in our study. It is possible that interpretation of other waveform abnormalities would not be improved by our PALM. The additional cohort from March 2022 to July 2022 was included to increase the study's sample size although we had no specific target sample size for the study. We did not perform an a priori or interim power calculation because there was no basis for determining the sample size needed to see a given effect size as prior studies evaluating hemodynamic monitor interpretation performance in residents had not been performed. The study's sample size was a convenience sample in that we invited all the first-year trainees from both programs to participate in the study, and those who agreed to participate were included. Although subjects were recruited from 2 large residency training programs, the overall sample size was small, and dropout was present. Participation in the study was voluntary, and the residents were informed that they could drop out at any time for any reason. The 3 residents in the PALM group who did not complete the PALM did not provide us with a reason for their drop out. The 3 residents in the control group who completed parts of the PALM did so by mistake. The PALM and all individual tests were housed on the same study website, and the 3 residents who mistakenly completed parts of the PALM simply clicked on the incorrect link. The technical problem that prevented 2 residents from finishing beyond the pretest was the result of a temporarily broken link on the study website. We undertook a per-protocol analysis as our primary goal was to evaluate the maximum potential efficacy of the PALM at 1 month when used as intended. For this reason, we only included in the final analysis those residents who strictly adhered to the study's protocol by completing the PALM and all required tests. We acknowledge that the use of per-protocol analysis is associated with possible limitations. Specifically, the loss of some residents and exclusion of others reduced the study's total sample size, leading to wider confidence intervals and an increased risk of type II errors.

The loss of these residents also introduced selection bias. The total attrition/exclusion rate for the study was 34.1% (14/41). The control group had a much higher attrition/exclusion rate of 52.4% (11/21), whereas the PALM group had an exclusion rate of 15.0% (3/20). Although all study participants were novice first-year anesthesiology residents with similar pretest scores between groups, it is possible that the residents who left or were excluded were different from those who did not leave or were excluded. For example, those residents who were more motivated or interested in the study's content may have been more likely to continue through to the delayed test. This factor may lead to overestimation of the impact of our PALM and limit the external validity of our findings. We observed statistically significant differences between groups with large effect sizes, indicating that the study's power was sufficient. Future studies with larger sample sizes including additional residency programs are needed to confirm our findings. Institutional variability in introductory anesthesia rotations and intraoperative shadowing may have also contributed to results as there may be differences in clinical exposure when completing the tests at differing months of the year. It may also be meaningful to study if the PALM intervention would have an impact on the learning process if instituted after, not before, basic hemodynamic introductory lectures. The magnitude of results on differences between the PALM and control groups were confounded by ongoing or differences in learning that may have occurred between the pretest and the delayed test. There was no standardization or comparison of the educational curriculum that the residents received during their introductory rotation between the pretest and delayed test. Similarly, we did not perform a time-matched control or active control group as our study was designed to examine the impact of the PALM relative to the normal teaching that novices receive during an introductory clinical anesthesia rotation (ie, the standard of care). No faculty members or others involved in the residents' education knew which residents were assigned to which group. Compared with the prior TEE study, this study did not examine the longer term impact (6 months to 1 year) as the

continued on next page

continued from previous page

delayed test was conducted 1 month after PALM intervention. Finally, the PALM group spent, on average, 15.9 minutes on the PALM itself, representing additional time on task compared with the control group. We think that the difference in time was small relative to the total learning time on the clinical rotation and that the differences in learning primarily relate to the perceptual nature of the learning occurring during the PALM. Nevertheless, it is possible that this additional time that the PALM group received could have also contributed to the differences between the groups on the delayed test. If this small amount of additional time on task caused such a large outcome difference at 1 month, then completing the hemodynamic monitor PALM seems well worth the time investment.

In conclusion, use of the hemodynamic monitor PALM produced significant, prolonged improvement in the accuracy and fluency in diagnosing clinical abnormalities by first-year anesthesiology residents. The hemodynamic monitor PALM can be used to enhance the interpretation of waveform abnormalities in novices.

Acknowledgments

We are grateful to the residents and faculty in the Department of Anesthesiology and Perioperative Medicine at UCLA and the Department of Anesthesiology and Pain Management at UTSW who assisted with this study. In addition, we are indebted to Cory Soto, CPhT, CHSOS (Simulation Center, David Geffen School of Medicine, UCLA), for help with recording video clips and to Timothy Burke, Matthew Baldrige, and Dara Afraz (Department of Psychology, UCLA) for their contributions in programming the hemodynamic monitor PALM and developing and maintaining the interface for acquiring and displaying subject performance data.

References

1. Martinelli SM, Isaak RS, Schell RM, et al. Learners and luddites in the twenty-first century: bringing evidence-based education to anesthesiology. *Anesthesiology* 2019;131:908-28.
2. Komasawa N, Berg BW. Simulation-based airway management training for anesthesiologists—a brief review of its essential role in skills training for clinical competency. *J Educ Perioper Med*. 2017;19:E612.
3. Gold JI, Watanabe T. Perceptual learning. *Curr Biol.* 2010;20:R46-8.
4. Roca A, Williams AM. Expertise and the interaction between different perceptual-cognitive skills: implications for testing and training. *Front Psychol.* 2016;7:792.
5. Krasne S, Stevens CD, Kellman PJ, Niemann JT. Mastering electrocardiogram interpretation skills through a perceptual and adaptive learning module. *AEM Educ Train.* 2020;5:e10454.
6. Kellman PJ, Garrigan P. Perceptual learning and human expertise. *Phys Life Rev.* 2009;6:53-84.
7. Mettler E, Kellman PJ. Adaptive response-time-based category sequencing in perceptual learning. *Vision Res.* 2014;99:111-23.
8. Kellman PJ, Krasne S. Accelerating expertise: perceptual and adaptive learning technology in medical learning. *Med Teach.* 2018;40:797-802.
9. Kellman PJ, Massey CM. Perceptual learning, cognition, and expertise. In: Ross BH, ed. *The Psychology of Learning and Motivation*, 1st ed. Academic Press Elsevier; 2013:117-65.
10. Mettler E, Massey CM, Kellman PJ. A comparison of adaptive and fixed schedules of practice. *J Exp Psychol Gen.* 2016;145:897-917.
11. Krasne S, Hillman JD, Kellman PJ, Drake TA. Applying perceptual and adaptive learning techniques for teaching introductory histopathology. *J Pathol Inform.* 2013;4:34.
12. Romito BT, Krasne S, Kellman PJ, Dhillon A. The impact of a perceptual and adaptive learning module on transoesophageal echocardiography interpretation by anaesthesiology residents. *Br J Anaesth.* 2016;117:477-81.
13. Rimoin L, Altieri L, Craft N, et al. Training pattern recognition of skin lesion morphology, configuration, and distribution. *J Am Acad Dermatol.* 2015;72:489-95.
14. Slaught C, Madu P, Chang AY, et al. Novel education modules addressing the underrepresentation of skin of color in dermatology training. *J Cutan Med Surg.* 2022;26:17-24.
15. Connor CW, Segal S. The importance of subjective facial appearance on the ability of anesthesiologists to predict difficult intubation. *Anesth Analg.* 2014;118:419-27.
16. Soeding P, Eizenberg N. Review article: anatomical considerations for ultrasound guidance for regional anesthesia of the neck and upper limb. *Can J Anaesth.* 2009;56:518-33.
17. Seligman KM, Weiniger CF, Carvalho B. The accuracy of a handheld ultrasound device for neuraxial depth and landmark assessment: a prospective cohort trial. *Anesth Analg.* 2018;126:1995-8.
18. Mulvey DA, Klepsch P. Use of processed electroencephalography in the clinical setting. *Curr Anesthesiol Rep.* 2020;10:480-7.
19. Bombardieri AM, Wildes TS, Stevens T, et al. Practical training of anesthesia clinicians in electroencephalogram-based determination of hypnotic depth of general anesthesia. *Anesth Analg.* 2020;130:777-86.
20. Morris RW, Watterson LM, Westhorpe RN, Webb RK. Crisis management during anaesthesia: hypotension. *Qual Saf Health Care.* 2005;14:e11.
21. Michard F, Kalkman CJ. Rethinking patient surveillance on hospital wards. *Anesthesiology* 2021;135:531-40.
22. Thiele RH, Durieux ME. Arterial waveform analysis for the anesthesiologist: past, present, and future concepts. *Anesth Analg.* 2011;113:766-76.
23. Kodali BS. Capnography outside the operating rooms. *Anesthesiology* 2013;118:192-201.
24. Patton K, Borshoff DC. Adverse drug reactions. *Anaesthesia* 2018;73(suppl 1):76-84.
25. Desciak MC, Martin DE. Perioperative pulmonary embolism: diagnosis and anesthetic management. *J Clin Anesth.* 2011;23:153-65.
26. Song Y, Chen N, Fang F. Effects of daily training amount on visual motion perceptual learning. *J Vis.* 2021;21:6.
27. Bang JW, Shibata K, Frank SM, et al. Consolidation and reconsolidation share behavioral and neurochemical mechanisms. *Nat Hum Behav.* 2018;2:507-13.
28. Moitra VK, Gabrielli A, Maccioli GA, O'Connor MF. Anesthesia advanced circulatory life support. *Can J Anaesth.* 2012;59:586-603.

continued on next page

continued from previous page

Jason S. Lee *is an Assistant Clinical Professor in the Department of Anesthesiology and Perioperative Medicine, Ronald Reagan University of California, Los Angeles, Medical Center, Los Angeles, CA;* ***Azad J. Hirpara*** *is a Staff Physician at Kaiser Permanente, Los Angeles, CA;* ***Sally Krasne*** *is a Professor Emeritus in the Department of Physiology, David Geffen School of Medicine at the University of California, Los Angeles, Los Angeles, CA;* ***Philip J. Kellman*** *is a Distinguished Professor in the Department of Psychology, University of California, Los Angeles, Los Angeles, CA;* ***John A. Kleinman*** *is a Staff Physician at Cottage Health, Santa Barbara, CA;* ***Boss Le*** *is a Resident Physician ss…sssin the Department of Anesthesiology, University of Southern California Keck School of Medicine, Los Angeles, CA;* ***Bryan T. Romito*** *is an Associate Professor in the Department of Anesthesiology and Pain Management, University of Texas Southwestern Medical Center, Dallas, TX.*

Corresponding author: *Bryan T. Romito, MD, MBA, Department of Anesthesiology and Pain Management, University of Texas Southwestern Medical Center, 5323 Harry Hines Boulevard, Dallas, TX 75390-9068. Telephone (214) 648-6165.*

Email address: *Bryan T. Romito: bryan.romito@utsouthwestern.edu*

Financial disclosure: *This work was supported by a grant from the National Cancer Institute at the National Institutes of Health (number 5R01CA236791-03) to Philip J. Kellman, PhD, and Sally Krasne, PhD.*

Conflicts of interest*: Philip J. Kellman, PhD, is the president of Insight Learning Technology Inc. and the author of patents on adaptive and perceptual learning technologies. All other authors declare no competing interests.*

Abstract

Background: Perceptual and adaptive learning modules (PALMs) are educational tools designed to enhance pattern recognition and long-term memory. We evaluated the impact of a hemodynamic monitor PALM on first-year anesthesiology residents' performance in diagnosing clinical abnormalities via waveform and vital sign interpretation on simulated monitors.

Methods: First-year residents were randomly assigned to a group (n = 20) that used the hemodynamic monitor PALM or a control group (n = 21) that did not. Both groups received a pretest that measured their accuracy and fluency (percentage of responses that were both accurate and made within a target response time) in hemodynamic monitoring interpretation. The PALM group then completed the PALM and an immediate posttest within 30 minutes. The Control group only completed an immediate posttest within 30 minutes. Both groups received a delayed test after 1 month. Accuracy and fluency in diagnosing clinical abnormalities at 1 month were the primary outcomes.

Results: Pretest accuracy and fluency were similar between the 2 groups. The PALM group accuracy (mean = 87% ± 3%) and fluency (mean = 64% ± 4%) were statistically significantly better than the control group accuracy (mean = 67% ± 6%, $P = .001$, $d = 1.39$) and fluency (mean = 45% ± 6%, $P = .01$, $d = 1.11$) in diagnosing clinical abnormalities at 1 month.

Conclusions: Exposure to a hemodynamic monitor PALM significantly improved the accuracy and fluency in diagnosing clinical abnormalities in a group of first-year anesthesiology residents at 1 month. The hemodynamic monitor PALM can be used to enhance the interpretation of waveform abnormalities in novices.

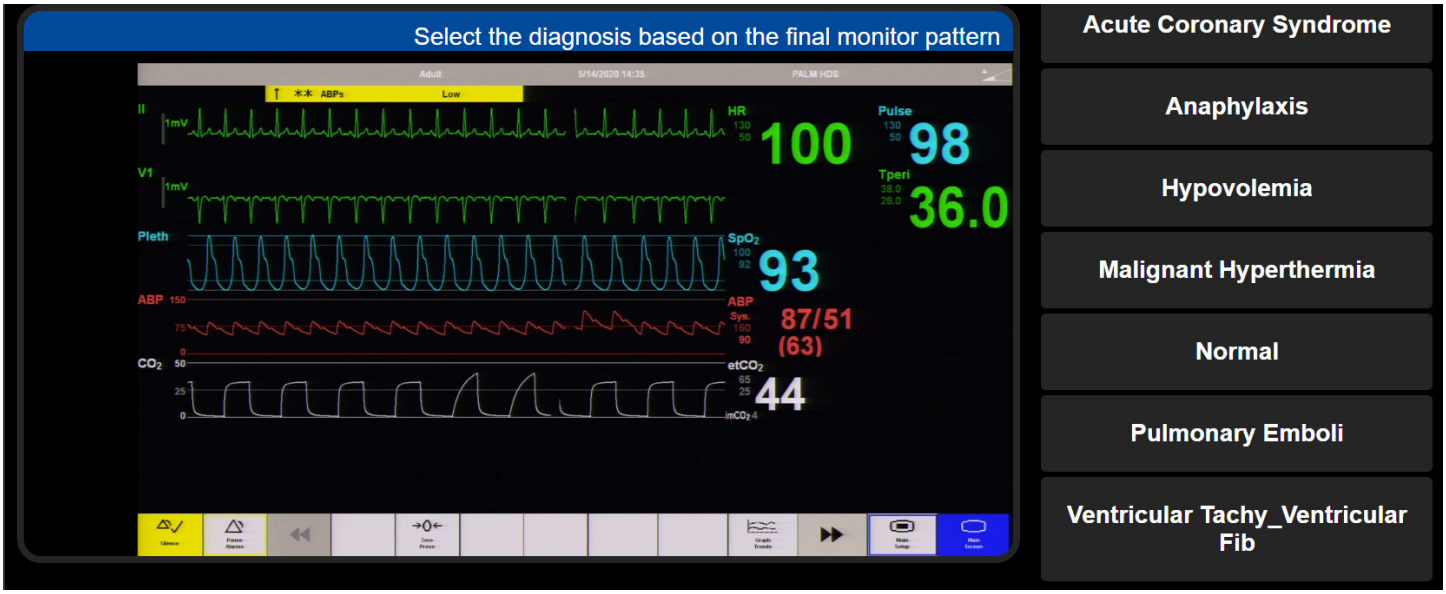
Keywords: Anesthesiology, education, hemodynamics, learning

continued on next page

continued from previous page

Figures

Figure 1. *Sample test item. This item displays the waveform changes associated with the diagnosis of anaphylaxis. Note the shark-tooth pattern developing on the capnogram with associated hypoxemia and hypotension.*

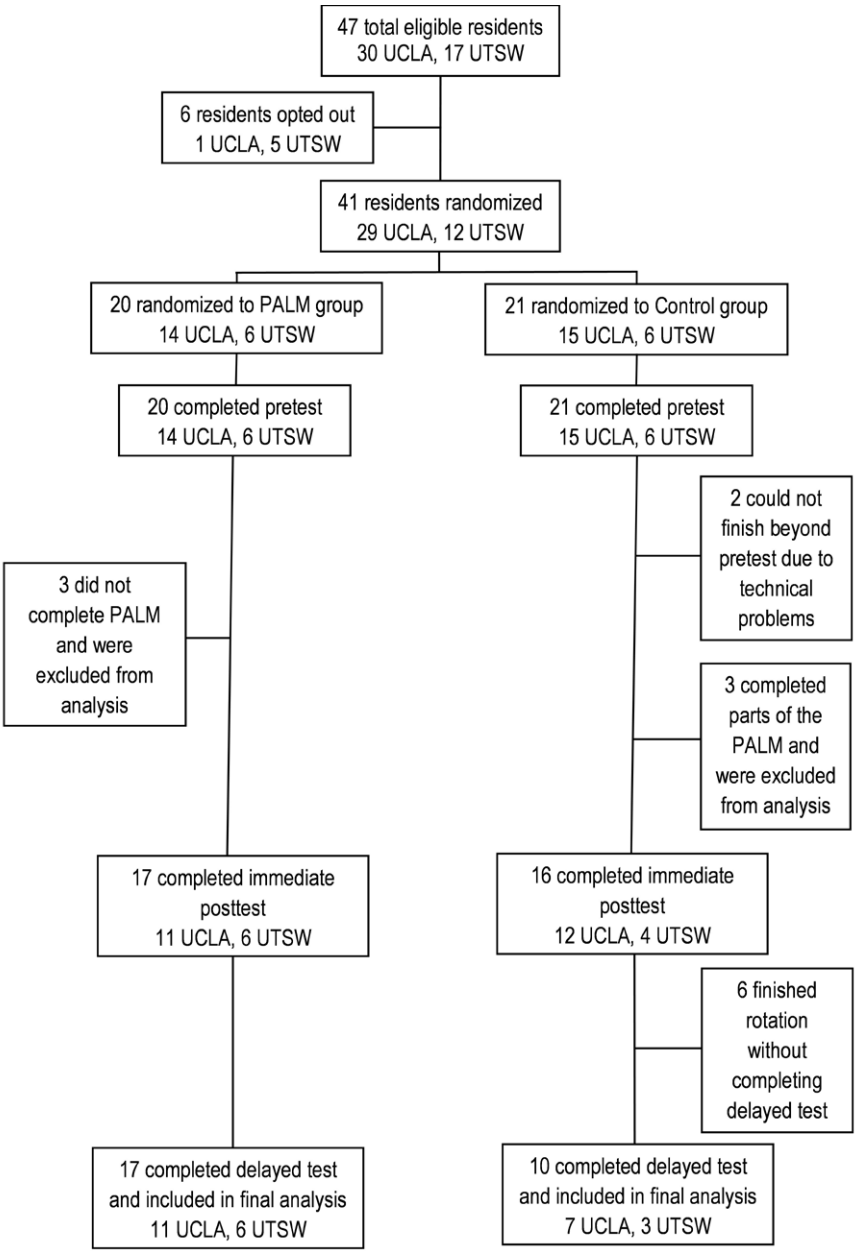


continued on next page

continued from previous page

Figures

Figure 2. *Study flow diagram. Abbreviations: PALM, perceptual and adaptive learning module.*

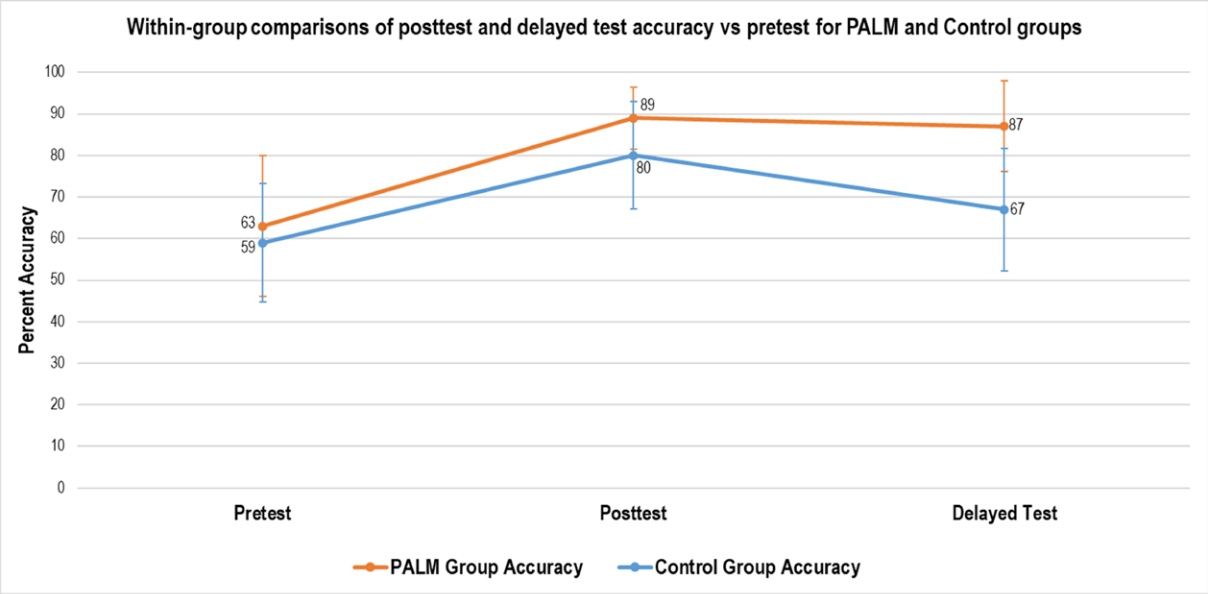


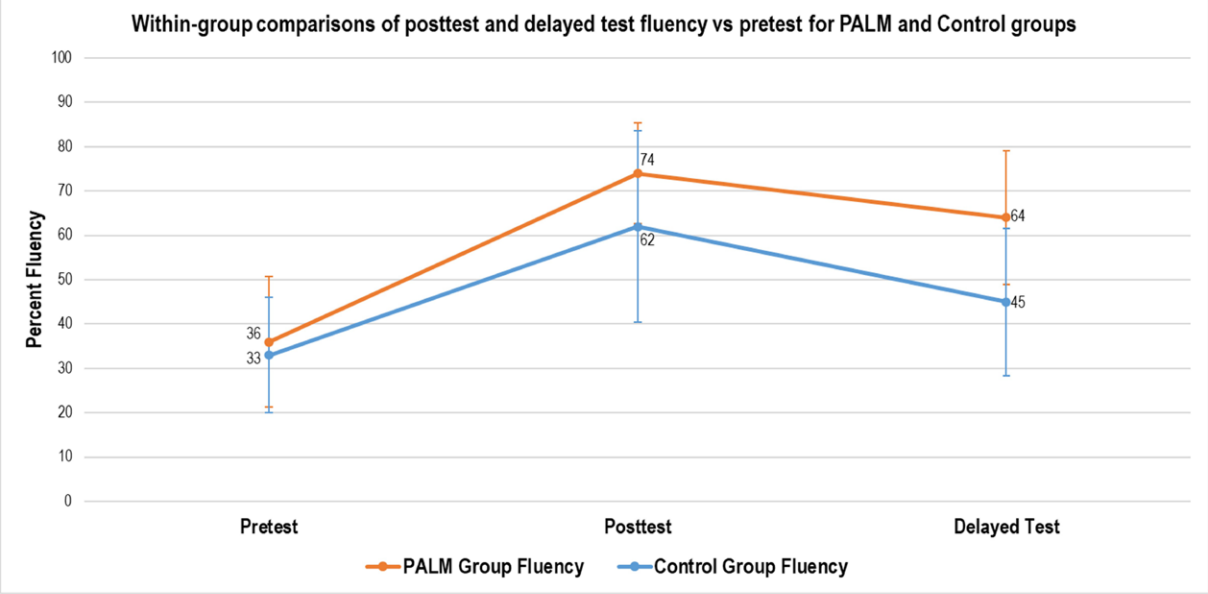
continued on next page

continued from previous page

Figures

Figure 3. *Within-group comparisons of posttest and delayed test performance vs pretest for PALM and control groups. Accuracy is displayed in the top set of graphs, whereas fluency is displayed in the bottom set of graphs. Points represent mean percentages, and colored error bars indicate ±1 SD for each corresponding group. Accuracy and fluency improved significantly from pretest to immediate posttest for both groups. At the delayed test, mean performance for the PALM group remained statistically significantly better compared with pretest for both accuracy (87% ± 3%, $p < .0001$, $d = 2.1$) and fluency (64% ± 4%, $p < .0001$, $d = 1.9$) with persistently large effect sizes, whereas the control group scores were not. $N_{PALM} = 17$ for all comparisons. $N_{Control} = 16$ for pretest to posttest comparisons. $N_{Control} = 10$ for pretest to delayed test comparisons. Abbreviations: PALM, perceptual and adaptive learning module.*



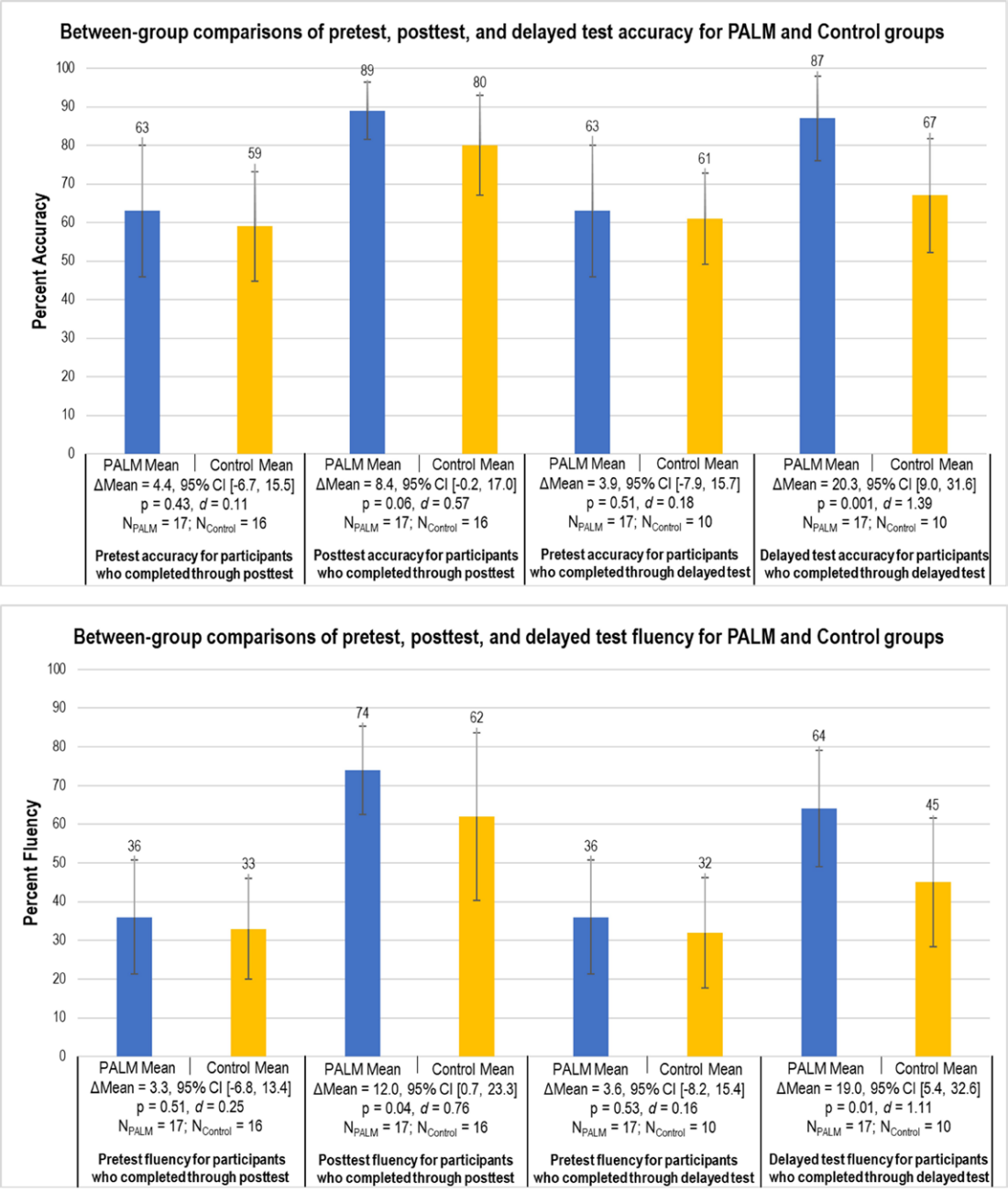


continued on next page

continued from previous page

Figures

Figure 4. *Between-group comparisons of pretest, posttest, and delayed test performance for PALM and control groups. Accuracy is displayed in the top set of graphs, whereas fluency is displayed in the bottom set of graphs. Bar heights represent mean percentages, and error bars indicate ±1 SD. As shown in the rightmost bar comparisons, the differences on the delayed tests between the PALM and control groups were statistically significantly greater with large effect sizes (accuracy, 87% ± 3% vs 67% ± 6%, p = .001, d = 1.39; fluency, 64% ± 4% vs 45% ± 6%, p = .01, d = 1.11). Abbreviations: PALM, perceptual and adaptive learning module; ΔMean, difference between PALM and control means; CI, confidence interval; d, effect size; N, number of participants.*



continued on next page

continued from previous page

Tables

Table 1. *Descriptions Associated With Each of the Training Sample Tracings in the Tutorial Slide Show Given to PALM and Control Groups*

Diagnosis	Description
Normal	All vital signs are within normal range.
Acute coronary syndrome	When cardiac ischemia occurs, you will notice ST segment changes on ECG, such as ST segment depression or elevation. Heart rate change is variable. Ischemia results in a loss of cardiac output resulting in hypotension and relative drop in end-tidal carbon dioxide.
Anaphylaxis	Unique to this pathology is the upslope shark tooth capnogram, following increase in heart rate, and indicating an obstructive process such as bronchospasm, which causes hypoxemia. End-tidal carbon dioxide will be high or low, depending on severity of obstruction and ability to ventilate, and on cardiac output. For severe bronchospasm, inability to ventilate results in flat capnogram. Anaphylaxis results in hypotension and often compensatory sinus tachycardia.
Hypovolemia	With a sudden decrease in preload and blood pressure, there is a compensatory relative tachycardia. End-tidal carbon dioxide is relatively decreased as well due to reduction in cardiac output.
Malignant hyperthermia	Unique to this pathology is the rise in temperature and significant increase in end-tidal carbon dioxide from the hypermetabolic state. It is often accompanied by tachycardia and hypotension.
Pulmonary embolism	The embolism causes hypoxemia and dead space ventilation from $\dot{V}_A/\dot{Q}$ mismatch, reflected by low oxygen saturation measured by pulse oximetry (Spo_2) and drop in end-tidal carbon dioxide. An obstructive lesion can cause a reduction in cardiac output and right heart strain, reflected by hypotension, relative tachycardia, and inferior lead T wave inversions and/or right bundle branch block on ECG.
Ventricular tachycardia/ ventricular fibrillation	The ECG shows the change to a nonperfusing heart rhythm, which is accompanied by a sudden drop in blood pressure and loss of end-tidal carbon dioxide. Because of lack of perfusion, a reliable Spo_2 reading is unobtainable.

Abbreviations: ECG, electrocardiogram; PALM, perceptual and adaptive learning module; Spo_2, oxygen saturation measured by pulse oximetry; $\dot{V}_A/\dot{Q}$, ventilation/perfusion.

Table 2. *Number of Attempts Necessary for PALM Group Participants to Retire Individual Categories*

Category	Total Attempts	Average Attempts	Range of Attempts
Acute coronary syndrome	132	7.8	4-15
Anaphylaxis	124	7.3	4-12
Hypovolemia	119	7.0	4-12
Malignant hyperthermia	61	3.6	3-4
Normal	61	3.6	3-4
Pulmonary embolism	73	4.3	3-6
Ventricular tachycardia/ventricular fibrillation	51	3.0	3-3

Abbreviation: PALM, perceptual and adaptive learning module.

continued on next page

continued from previous page

Tables

Table 3. *Category Sensitivity and Specificity by Test Phase and Participant Group*

	Sensitivity					
	PALM (%)			Control (%)		
Test category	Pre	Post	Delayed	Pre	Post	Delayed
Acute coronary syndrome	76.5	94.1	91.2	59.4	84.4	50.0
Anaphylaxis	26.5	91.2	79.4	25.0	62.5	45.5
Hypovolemia	44.1	82.4	82.4	43.8	56.3	50.0
Malignant hyperthermia	73.5	97.1	97.1	59.4	87.5	90.9
Normal	88.2	97.1	91.2	93.8	96.9	95.5
Pulmonary embolism	50.0	58.8	76.5	65.6	78.1	59.1
Ventricular tachycardia/ ventricular fibrillation	85.3	100.0	94.1	81.3	96.9	95.5
Overall	63.4	88.7	87.4	58.9	80.4	67.1
P (within group)		0.02	0.01		0.01	0.19
ΔMn ± CI (%)		25.2, 95% CI [6.5, 43.9]	24.0, 95% CI [7.9, 40.1]		19.2, 95% CI [8.4, 30.0]	8.3, 95% CI [-5.3, 21.9]
	Specificity					
	PALM (%)			Control (%)		
Test category	Pre	Post	Delayed	Pre	Post	Delayed
Acute coronary syndrome	99.0	97.5	99.0	95.8	99.0	99.2
Anaphylaxis	93.1	98.5	98.0	93.8	96.9	92.5
Hypovolemia	91.2	93.6	97.5	92.2	93.2	87.5
Malignant hyperthermia	99.0	100.0	98.5	99.0	100.0	99.2
Normal	95.1	99.5	99.5	94.8	96.4	95.8
Pulmonary embolism	91.2	98.5	96.6	89.6	94.8	89.2
Ventricular tachycardia/ ventricular fibrillation	98.5	100.0	99.0	99.5	100.0	100.0
Overall	67.2	87.7	88.2	64.6	80.2	63.3
P (within group)		0.04	0.03		0.01	0.85
ΔMn ± CI (%)		2.9, 95% CI [0.1, 5.7]	3.0, 95% CI [0.3, 5.7]		2.2, 95% CI [0.6, 3.8]	0.9, 95% CI [-1.4, 3.2]

Abbreviations: CI, confidence interval; PALM, perceptual and adaptive learning module; ΔMean, difference between PALM and control means.