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Online Learning and Residents' Acquisition of Mechanical Ventilation Knowledge: Sequencing Matters

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Objective: Rapid advancements in medicine and changing standards in medical education require new, efficient educational strategies. We investigated whether an online intervention could increase residents' knowledge and improve knowledge retention in mechanical ventilation when compared with a clinical rotation and whether the timing of intervention had an impact on overall knowledge gains.

Design: A prospective, interventional crossover study conducted from October 2015 to December 2017.

Setting: Multicenter study conducted in 33 PICUs across eight countries.

Subjects: Pediatric categorical residents rotating through the PICU for the first time. We allocated 483 residents into two arms based on rotation date to use an online intervention either before or after the clinical rotation.

Interventions: Residents completed an online virtual mechanical ventilation simulator either before or after a 1-month clinical rotation with a 2-month period between interventions.

Measurements and Main Results: Performance on case-based, multiple-choice question tests before and after each intervention was used to quantify knowledge gains and knowledge retention. Initial knowledge gains in residents who completed the online intervention (average knowledge gain, 6.9%; SD, 18.2) were noninferior compared with those who completed 1 month of a clinical rotation (average knowledge gain, 6.1%; SD, 18.9; difference, 0.8%; 95% CI, –5.05 to 6.47; $p = 0.81$). Knowledge retention was greater following completion of the online intervention when compared with the clinical rotation when controlling for time (difference, 7.6%; 95% CI, 0.7–14.5; $p = 0.03$). When the online intervention was sequenced before (average knowledge gain, 14.6%; SD, 15.4) rather than after (average knowledge gain, 7.0%; SD, 19.1) the clinical rotation, residents had superior overall knowledge acquisition (difference, 7.6%; 95% CI, 2.01–12.97; $p = 0.008$).

Conclusions: Incorporating an interactive online educational intervention prior to a clinical rotation may offer a strategy to prime learners for the upcoming rotation, augmenting clinical learning in graduate medical education. (*Crit Care Med* 2019; XX:00–00)

Key Words: flipped classroom; graduate medical education; mechanical ventilation; online learning; pediatric critical care medicine; virtual simulation

Medical education faces growing challenges across the continuum of training. The 20th century model of learning through lectures followed by hospital-based apprenticeships is increasingly ill-suited to meet 21st century demands (1–5). Exponential growth of medical knowledge and clinical data exceed what humans can learn, thus challenging existing paradigms of medical education (6–8). In graduate medical education (GME), time available for clinical teaching (9–11) and exposure to clinical variety is limited (12), in part due to work hour restrictions (13–15). New mandates for competency-based education create additional pressure to change educational approaches to improve efficiency and effectiveness (3, 16). To address these emerging challenges, many educators are turning to online educational tools to augment the clinical training environment.

Online learning technologies enable learning in ways unachievable through traditional instructional methods by overcoming barriers of time, distance, and randomness of the apprenticeship model (10, 17, 18). Online learning can standardize instruction, provide individualized and immediate feedback, and allow learners to review educational materials (10). Online learning activities promote knowledge gains across training levels and disciplines (19) and are particularly beneficial if they support, but not replace, face-to-face experiences (18). Despite potential benefits, effective integration of online learning to augment traditional graduate clinical rotations remains understudied.

We designed the Game-based Education in Residency (GamER) Study to determine the efficacy of incorporating an interactive online educational intervention to augment resident learning during a clinical rotation. We hypothesized that an online intervention would increase residents' knowledge in mechanical ventilation and would be noninferior to a clinical rotation. We also aimed to investigate the effect of each intervention on knowledge retention and to evaluate if the timing of the intervention had an impact on overall knowledge gains.

MATERIALS AND METHODS

Study Design

From October 2015 to December 2017, we conducted a prospective, crossover, interventional study evaluating changes in mechanical ventilation knowledge in pediatric residents rotating through the PICU who used an online virtual mechanical ventilation simulator either before or after the clinical rotation.

Participants and Settings

We included residents rotating through the PICU for the first time during residency from 33 centers in eight countries, across five continents. We excluded residents who had previously rotated through the PICU during residency training, were part of a combined residency program (i.e., Internal Medicine-Pediatrics), or if there was not enough time between potential date of enrollment and start of clinical rotation to complete the intervention. A central study coordinator allocated residents in blocks by clinical rotation date into one of two arms (Clinical Rotation First or Simulator First). This study was approved by the Institutional Review Board at all sites.

Interventions

We developed an online mechanical ventilation simulator designed to teach principles of mechanical ventilation across various patient ages and disease states (https://www.openpediatrics.org/assets/simulator/ventilator-simulator). The simulator includes three sections of increasing difficulty that learners must complete sequentially: Knowledge Guide, Tactics, and Cases (**Supplemental Fig. 1**, Supplemental Digital Content 1, http://links.lww.com/CCM/F19) (20). The Knowledge Guide teaches learners how to set up and adjust a mechanical ventilator based on clinical data. The Tactics section contains short problems, such as hypoxemia, requiring the learner to systematically interpret clinical information to identify and perform maneuvers that solve the problems. The Cases section allows the learner to care for simulated patients with less structured guidance. In the Tactics and Cases sections, the learner receives hints and feedback about actions and progresses when problems are correctly solved. The simulator was accessed on the OPENPediatrics EdX platform (EdX, Boston, MA).

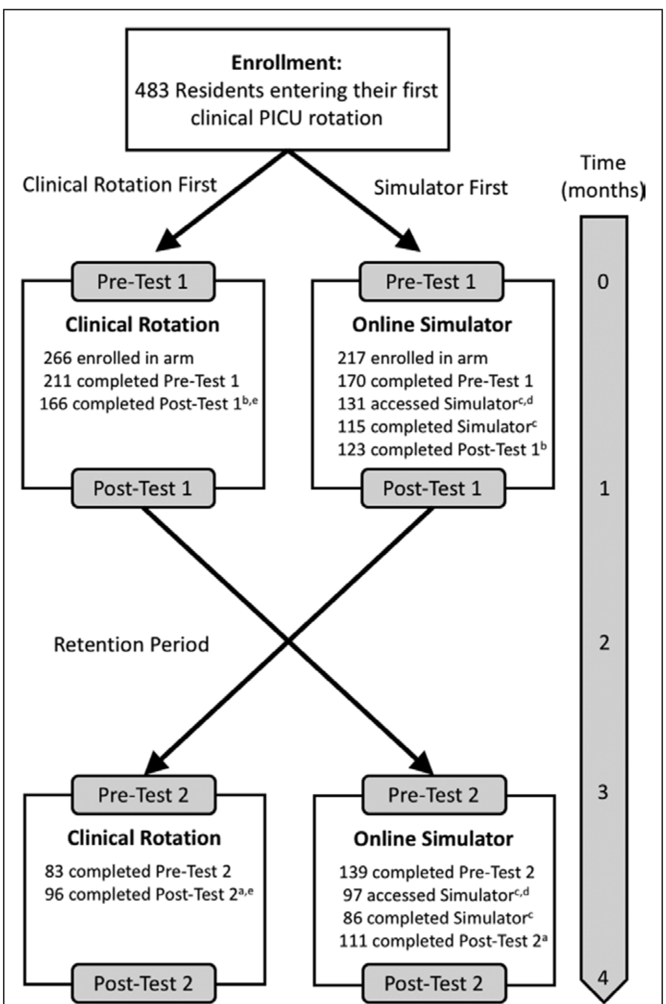

Figure 1. Game-Based Education in Residency Study schematic. [a]Residents who completed the study; [b]residents included in **Table 1**; [c]residents included in the simulator use section; [d]residents included in the resident satisfaction section; and [e]residents included in the clinical rotation experience section.

All residents rotated through their scheduled clinical rotation and were assigned the simulator for 4 weeks (**Fig. 1**). We requested that site investigators make no alterations in the clinical rotation or mechanical ventilation teaching during the study period. Residents in the Clinical Rotation First arm completed their scheduled clinical rotation and were then assigned the simulator 2 months after rotation completion. Residents in the Simulator First arm were assigned the simulator and then completed their clinical rotation 2 months after simulator use. We planned a 2-month period between interventions to evaluate knowledge retention from the first intervention.

Instruments

We developed a case-based, multiple-choice question test to assess mechanical ventilation knowledge by adapting questions from the literature (21–23). Five pediatric intensivists evaluated the questions for accuracy, providing content validity evidence. To collect construct validity evidence, we administered the test to groups of medical students, residents, and pediatric critical care fellows and attending physicians (20 total, five per group). Data showed good differentiation between training levels ($p < 0.001$) (**Supplemental Table 1**, Supplemental Digital Content 2, http://links.lww.com/CCM/F20), but prompted the removal of five questions for poor performance.

The remaining questions were used to develop four separate tests, each composed of 15 questions, which were administered in different sequences to minimize effect of test order. To determine internal consistency, we performed Hoyt analysis and found excellent internal validity with reliability coefficients $r =$ 0.96, 0.89, 0.93, and 0.94 for each test.

We developed a survey instrument to assess resident satisfaction with the interventions, feedback about the simulator, (in)formal education received about mechanical ventilation prior to and during the study, and time spent caring for mechanically ventilated patients during the clinical rotation.

Study Procedures

Figure 1 outlines study procedures. Residents completed Pre-Test 1 to assess baseline knowledge, then completed the first intervention and were tested with Post-Test 1. After 2 months, residents completed Pre-Test 2 to assess knowledge retention and completed Post-Test 2 after the second intervention to assess overall knowledge gains. Only residents who completed the appropriate pretest were assigned the simulator. We removed residents who did not complete the pre- and/or posttests per the required timeline from the study. We administered feedback surveys concurrently with each posttest and delivered all surveys and tests via email utilizing SurveyMonkey (Palo Alto, CA).

Analysis

We used a noninferiority approach to calculate sample size for our primary hypothesis that knowledge gains would be noninferior in residents using the simulator when compared with the clinical rotation. Our a priori power analysis specified that 84 residents per arm provided 80% power within a 12-point margin for a difference of 3.5 between means with an SD of 21.9 and α of 0.05.

We calculated frequencies and percentages for resident and site characteristics and compared data between arms using chi-square or Fisher exact test as appropriate. We assessed normality of continuous data using the Shapiro-Wilk test. Because all continuous data were normally distributed, we reported test scores as mean percentages (out of 100%) and SDS. We used a two-sided α of 0.05 to determine statistical significance. We included residents who completed all tests and the simulator in the analyses unless otherwise indicated. Residents were considered simulator completers if they completed at least the entire Knowledge Guide.

To investigate initial knowledge gains, we compared mean differences in test scores before and after first intervention in each arm using 95% CIs and paired *t* tests. To evaluate knowledge retention, we performed multivariable linear regression modeling to control for differences in duration of retention period time among residents, which occurred because of test completion delays. We used independent groups *t* test to compare mean differences in time between arms. To investigate overall knowledge gains at study completion, we compared mean differences in scores between baseline and final test using 95% CIs and paired *t* tests.

We used multivariable generalized estimating equation (GEE) modeling to consider repeated measures within a resident, assess changes in test scores over the study, and adjust for confounding with the following variables: rotation length greater than 4 weeks, presence of respiratory therapists, year of residency training, previous training in mechanical ventilation, number of months spent in a neonatal ICU (NICU) rotation during residency, number of months spent in any ICU rotation during medical school, English as a primary language, and simulator completion. We included residents who completed all four tests regardless of simulator completion.

We used simulator learning analytics to capture progress and time spent using the simulator, descriptive statistics to report duration of simulator use, the Wilcoxon rank-sum test to analyze differences between arms, and bootstrap resampling to determine 95% CIs for differences between medians. We compared perceived satisfaction using chi-square test and calculated frequencies and percentages for survey responses about clinical rotation education and simulator feedback.

We used Stata version 15.0 (StataCorp, College Station, TX) for all statistical analyses except for power calculations which were performed using PASS version 13 (NCSS Statistical Software, Kaysville, UT).

RESULTS

Of the 483 residents enrolled in the study, 207 (43%) completed the study, equally distributed across both arms (Fig. 1). Characteristics of residents, training programs, and PICUs were similar between arms (**Table 1**), except for a difference in the number of PICUs with respiratory therapists (more common in the Clinical Rotation First arm).

Educational Outcomes

Residents' knowledge increased following first intervention in both arms, and we found no statistically significant difference in test scores between arms (**Fig. 2**; **Table 2**). When

TABLE 1. Resident, Training Program, and PICU Characteristics

Resident, Training Program, and PICU Characteristics	Clinical Rotation First Arm (*n* = 166), *n* (%)	Simulator First Arm (*n* = 123), *n* (%)	*p*
Gender			0.973
Female	109 (66)	81 (66)	
Age, yr			0.785
22–25	19 (11)	14 (11)	
26–28	84 (51)	67 (54)	
> 28	63 (38)	42 (34)	
Year of pediatric training			0.264
First	51 (31)	29 (24)	
Second	78 (47)	58 (47)	
Third or greater	37 (22)	36 (29)	
Rotation length, wk			0.693
4	105 (63)	75 (61)	
> 4	61 (37)	48 (39)	
Previous mechanical ventilation teaching			0.159
Yes	127 (77)	85 (69)	
No. of months spent in a neonatal ICU rotation during residency			0.194
0	26 (16)	28 (23)	
1–2	103 (63)	64 (53)	
≥ 3	35 (21)	29 (24)	
No. of months spent in an ICU rotation during medical school			0.976
0	109 (66)	80 (65)	
1–2	50 (30)	38 (31)	
≥ 3	7 (4)	5 (4)	
Possible career in Critical Care Medicine?			0.442
Yes	48 (29)	28 (23)	
No	82 (49)	69 (56)	
Unsure	36 (22)	26 (21)	
No. of pediatric residents in the training program			0.227
< 50	54 (32)	33 (27)	
50–99	59 (35)	56 (45)	
≥ 100	53 (32)	34 (28)	
No. of beds in the PICU			0.451
≤ 12	28 (17)	15 (13)	
13–20	59 (35)	42 (35)	
> 20	79 (48)	66 (54)	
Respiratory therapists present in PICU			**0.005**
Yes	130 (78)	78 (63)	
English spoken as primary language to conduct medicine in the PICU			0.278
Yes	145 (87)	101 (82)	

Boldface value indicates $p < 0.05$.

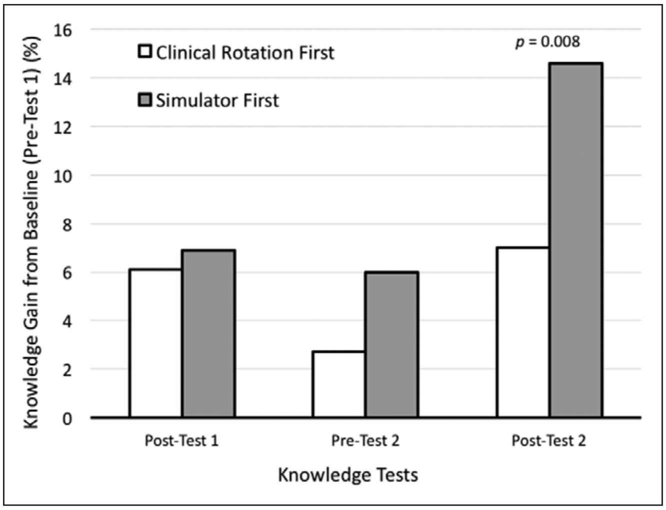

Figure 2. Change in test scores throughout the study by arms.

controlling for time in multivariable linear regression modeling, we observed that knowledge retention after first intervention was significantly greater following the simulator when compared with the clinical rotation (difference, 7.6%; 95% CI, 0.7–14.5; $p = 0.03$). We found a significantly higher mean difference in final test scores between baseline and final test in the Simulator First arm when compared with the Clinical Rotation First arm (Table 2). Due to test completion delays by residents, we observed a difference in average duration of time between Post-Test 1 and Pre-Test 2 between arms, Simulator First arm (35 d; SD, 19 d), and Clinical Rotation First arm (63 d; SD, 14 d) (difference, 28 d; 95% CI, 23–30; $p < 0.001$, data not shown).

Multivariable GEE modeling performed for residents who completed all four tests confirmed the same univariate results as above (**Supplemental Table 2**, Supplemental Digital Content 3, http://links.lww.com/CCM/F21). Knowledge gain after first intervention was comparable between arms ($p = 0.84$), and overall knowledge gain at the end of study was greater in the Simulator First Arm when compared with the Clinical Rotation First arm ($p < 0.001$). Year of residency and previous training in mechanical ventilation were significant predictors of test scores, whereas rotation length greater than 4 weeks, presence of respiratory therapists, English primarily spoken in the hospital, previous NICU rotation in residency, and previous ICU rotation during medical school were not significant predictors. The majority of residents (56/73) who rotated through the PICU for the first time during year 3 or greater were residents training in teaching hospitals outside of the United States where the residency model is typically of a longer duration in years than the U.S. model. Residents who completed the simulator had higher test scores compared with residents who did not. There was no association between resident scores and the eight potential test sequences ($p = 0.45$).

TABLE 2. Differences in Test Scores by Study Arm

Study Element	Clinical Rotation First: Mean Test Score (SD)	Simulator First: Mean Test Score (SD)	Mean Difference in Scores (95% CI for Difference Between Arms)	*p*
Knowledge gain after first intervention				
n	89	72		
Pre-Test 1	47.5 (17.5)	44.6 (15.4)	−2.9 (−8.05 to 2.33)	0.28
Intervention	Clinical rotation	Simulator		
Post-Test 1	53.6 (17.6)	51.5 (17.0)	−2.1 (−7.59 to 3.28)	0.44
Knowledge gain	6.1 (18.9)	6.9 (18.2)	0.8 (−5.05 to 6.47)	0.81
Knowledge gain after second intervention				
n	89	72		
Pre-Test 2	50.2 (18.4)	50.6 (18.3)	0.4 (−5.3 to 6.19)	0.87
Intervention	Simulator	Clinical rotation		
Post-Test 2	54.5 (18.6)	59.2 (15.9)	4.7 (−0.83 to 10.11)	0.09
Knowledge gain	4.3 (16.5)	8.6 (15.8)	4.3 (−0.91 to 9.25)	0.11
Overall knowledge gain				
n	89	72		
Pre-Test 1	47.5 (17.5)	44.6 (15.4)	−2.9 (−8.05 to 2.33)	0.28
Post-Test 2	54.5 (18.6)	59.2 (15.9)	4.7 (−0.83 to 10.11)	0.09
Knowledge gain	7.0 (19.1)	14.6 (15.4)	7.6 (2.01–12.97)	**0.008**

All scores represent the mean percentage correct, out of a possible 100%.
Boldface value indicates $p < 0.05$.

Simulator Use

Of the 306 residents who completed the presimulator test and were assigned the simulator, 228 (75%) accessed the simulator, and 201 (66%) completed at least the Knowledge Guide, with no difference between arms (**Supplemental Table 3**, Supplemental Digital Content 4, http://links.lww.com/CCM/F22). Overall, residents spent a median of 5.25 hours (315 min; interquartile range, 204–451 min) using the simulator, with no difference between arms. In the subset of residents who were simulator completers, residents in the Simulator First arm spent 1 hour more using the simulator compared with the Clinical Rotation First arm.

The subset of residents who reported not using the simulator during the study described not having enough time or having other commitments (48%, 20/42) and technical difficulties (31%, 13/42) as most common barriers. Of the 228 residents who accessed the simulator, 196 residents (86%) responded to the postsimulator feedback survey about problems experienced when using the simulator. They responded with the following comment themes (residents were allowed multiple responses): no problems or praise (30%, 60/196), technical issues (25%, 49/196), difficult user interface/user experience (12%, 23/196), lack of feedback (11%, 22/196), difficulty setting alarms (7%, 13/196), insufficient time (5%, 10/196), content was too difficult (3%, 6/196), wanted more content (2%, 4/196), and simulator experience differed from their local practice (1%, 2/196).

Resident Satisfaction

Two hundred twenty-eight residents accessed the simulator as well as completed their clinical rotation. Seventy-six percent (175/228) of these residents responded to the simulator satisfaction question following the intervention, and 82% (188/228) responded to the clinical rotation satisfaction question. Residents reported greater satisfaction with the education received from the simulator than from the clinical rotation, with 73% (128/175) of residents reporting that they were "satisfied" or "very satisfied" with the simulator when compared with 61% (115/188) with the clinical rotation (difference, 12%; 95% CI, 3–21%; $p = 0.02$).

Clinical Rotation Experience

Two hundred sixty-two residents completed the clinical rotation and responded to the posttest. Eighty-nine percent (232/262) of residents reported receiving instruction or seeking resources on their own about mechanical ventilation. Informal bedside teaching was the most common modality (84%, 221/262) followed by didactic lectures (62%, 163/262) and articles (44%, 116/262). Overall, 37% (97/262) of residents reported spending greater than 20 hours per week on direct care of mechanically ventilated patients during their clinical rotation, with no difference between arms (36%, 35/96 Simulator First arm and 37%, 62/166 Clinical Rotation First arm; difference, 1%; 95% CI, –11% to 13%; $p = 0.89$).

DISCUSSION

We found that an interactive online educational intervention led to similar knowledge gains as a clinical rotation. Knowledge retention was greater following the online intervention when compared with the clinical rotation when controlling for time. When the online intervention was sequenced before rather than after the clinical rotation, residents had greater overall knowledge gains at the end of the study.

We observed equivalent knowledge acquisition from the simulator and clinical rotation aligning with studies reporting similar efficacy for technology-enhanced simulation interventions (24). We also demonstrated that the sequence of interventions impacted overall knowledge gains, suggesting that providing relevant education prior to a clinical rotation improves overall training effectiveness. We believe that our data not only support the integration of online learning activities into GME but also provide guidance for appropriate sequencing. Our approach finds support from three educational concepts: 1) flipped classroom; 2) experiential learning; and 3) mastery learning/deliberate practice.

The flipped classroom model encourages students to learn lessons traditionally taught in-person prior to class, followed by active learning in the classroom (1, 4, 25). Learners report satisfaction and increased motivation with this approach, but studies demonstrating effectiveness remain limited, especially in GME (25–28). Although there is limited structured "classroom" time in GME, there are many essential skills that must be learned and applied throughout a clinical rotation.

Despite emerging evidence supporting use of the flipped classroom model in GME, many programs have yet to formally incorporate this approach into practice, often attributed to lack of high-quality resources (29). Thus, collaborative development and sharing of online educational activities, as successfully performed in the current project, may help improve education worldwide (2, 18, 30).

A particular strength of our online intervention is the interactive nature which allows for experiential learning as learners actively participate in problem solving and case management. Experiential learning theories describe how learning occurs through reflection on concrete experiences, and subsequent active experimentation while applying new knowledge allows for translation of knowledge between contexts, which further augments learning (31). The virtual simulator is designed around principles of mastery learning: learners must master a topic before progressing to the next step and if unsuccessful, are provided assistance to facilitate learning (32, 33). In addition, the simulator promotes deliberate practice, which is focused, repetitive practice followed by feedback and reflection while acquiring skills of increasing difficulty (33, 34).

Both mastery learning and deliberate practice improve the development of expertise (35), and together with experiential learning, can explain the greater knowledge acquisition among residents who experienced the simulator before the clinical rotation. These residents gained knowledge from their experiences managing virtual patients and achieved mastery of increasingly complex scenarios through deliberate practice. In the virtual environment, they could care for more "patients" than the clinical environment allows, accelerating the development of expertise. Then, with support of experienced clinicians, they consolidated this acquired knowledge applying it to new patient care experiences in differing contexts during a clinical rotation, allowing earlier achievement of competency, and enhancing efficiency and efficacy of the clinical rotation. Motivation to prepare for an upcoming rotation also likely influenced our results because residents in the Simulator First arm spent nearly an hour more using the simulator.

Our study has several important limitations. First, we observed knowledge gains that increased by a minimum of 6.3% to a maximum of 14.5% between tests in both arms. Although these knowledge gains may seem small in absolute terms, they are consistent with the increase in knowledge reported in other studies in GME (12). We observed a difference in time from Post-Test 1 to Pre-Test 2 between arms related to residents' delays in test completion; however, multivariable linear regression modeling demonstrated that the relationship between time elapsed and resultant knowledge retention was not statistically different between arms. Therefore, the significant differences between arms reflected an independent relationship between time elapsed and resultant knowledge retention between arms. Third, the use of multiple-choice question tests to measure knowledge is an imperfect measure of learning. Ideally, we would have measured clinical outcomes, but as caring for mechanically ventilated patients is a team responsibility, we felt that it would be unrealistic to expect changes in patient outcomes following an intervention of a single provider group. Assessing care of simulated patients may have offered another approach, and we hope to conduct this assessment in future studies.

Additionally, our overall study completion rate was only 43%, similar to other studies in GME (36). Both learner and institution characteristics may affect noncompletion rate (37), and although learner characteristics and completion rates appeared similar between groups, we did not control for different "traditional teaching" practices across the sites. Although we have no reason to suspect any influence on systematic noncompletion, we also cannot exclude such bias. There may also have been differences in knowledge gains between residents who completed and those who did not complete the study. Finally, more respiratory therapists were present in the Clinical Rotation First arm. Although evidence exists that respiratory therapist presence can improve weaning of mechanical ventilatory support or oxygen titration table compliance (38, 39), little is known about the impact on resident learning, and the presence of respiratory therapists did not influence test scores in our GEE model.

CONCLUSIONS

Our data suggest that incorporating an interactive online educational intervention prior to a clinical rotation may offer a strategy to improve effectiveness of traditional clinical learning in GME. In the era of competency-based learning, appropriate sequencing of online resources may partially compensate for limitations in clinical exposure due to restricted duty hours and may help guide the development of more effective longitudinal curricular strategies for graduate medical learners. Sharing of online resources across institutions may help meet emerging educational demands for high-quality online learning resources.

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