Learning Curves in Bronchoscopy Simulation to Identify and Explain Patterns of Growth

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THESIS

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LIST OF ABBREVIATIONS

CCC	Clinical Competency Committees
CBME	Competency Based Medical Education
PI	Principal Investigator
SD	Standard Deviation
VR	Virtual Reality

ABSTRACT:

PURPOSE: Learning curves show how trainees acquire a skill. Unlike other forms of assessment that show whether the learning has occurred, learning curves show what the path to competence looks like. The aim of this study was to describe the learning curves of novice trainees while practicing on a Bronchoscopy Virtual Reality (VR) simulator and identify and explain patterns that may alert educators of trainees in difficulty.

METHODS: This was a sequential explanatory mixed methods design. In 2018, 20 Pediatric Critical Care and Respirology Subspeciality trainees as well as eight faculty practiced with the VR simulator. We looked at relationship between number of repetitions and VR outcomes and patterns of growth using a growth mixture modeling. Using a qualitative instrumental case study method we collected field notes and conducted semi-structured interviews with trainees and simulation instructor to explore the use of automatic scoring from the VR simulator, pattern of practice and strategies used for learning during the simulation practice. Constant comparative analysis was used to identify themes iteratively. Team analysis continued until a stable thematic structure was developed and applied to the entire data set.

RESULTS: Using a growth mixture modeling we statistically identified two patterns of growth. Eight out of twenty learners belonged to the group with a slower growth and plateau at a lower score. The field notes and interviews identified five out of eight learners in that group as the ones who had: inherent difficulty with the skill, did not integrate the knowledge of anatomy in simulation practice and used the simulator for simple repetitive practice with no strategy for improvement in between trials. The faster growing group used strategies of adaptive expertise.

CONCULSIONS: We provide validity evidence for use of growth models in education and explain patterns of growth such as a “slow growth” with a mechanistic repetitive practice and a “fast growth” with adaptive expertise.

1. INTRODUCTION

Competency Based Medical Education (CBME) has changed the perspective from a time-based, to an outcome-based and learner centered approach.[1] As the medical education community embraces toward CBME, there are several important challenges including: the lack of valid measures assessing competencies; whether competencies represent valid measurement constructs; tensions between competency frameworks and real-life holistic faculty assessments; and, how Clinical Competency Committees (CCC) select and synthesize the information on performance to judge and help residents' progression. [2,3,4,5] CBME has substantial implications for assessment. However, there are still calls for innovation in assessment and greater use of -and expertise in- education data analytics.[6,7,8]

Considering that learners come with variable skills and attain competencies with variable rates, it seems logical that the time needed to train will also be variable. If so, the assessment of progression must bear the consequences of accelerating or shortening training.[8] Learners' individualized progression and trajectories toward reaching competence, tracked by multiple assessments, their 'learning curves', represent the rate at which trainees acquire a skill.[9] Unlike other forms of assessment that tell whether learning has been achieved, learning curves illustrate the trajectory of the learning path and portray an example of assessment for learning. Learning curves may be used for descriptive purposes, showing the graphic relationship between effort (repetition, time) and performance for a given task, or to make predictions such as: indicate reassurance (for those on track), and to facilitate early detection for those in difficulty.[10]

Analysis of learning curves can refine our understanding of how trainees achieve competency. Similar approaches have been used extensively in public health and the clinical arena, and are now advocated for use in medical education.[11-13] Techniques for examining learning curves range from simple descriptive analysis of trends to more advanced multivariate methods. While the need and motivation for studying learning curves in CBME have been sufficiently documented, empirical analyses have been lacking. Data-driven, mathematical approaches may or may not be able to replace teacher's judgment just as they cannot replace clinical judgment.[14] Some important factors that affect the rate of learning might not be readily quantifiable (*e.g*. motivation, problem-solving ability, teacher-learner interactions, learners' use of data) and are observable only by teachers. Before widespread use of data analytics in medical education, more research is needed.

A mastery model of simulation-based training for procedural skills, offers a controlled setting for testing predictive analytics in education for the following reasons. *First*, mastery learning model is analogous to CBME.[15] Mastery learning focuses on demonstrated performance rather than on the time spent learning.[16] In a mastery-training model, the learner is provided with terminal objectives with predetermined proficiency, opportunities for study and practice, and repeated formative testing with feedback. *Second*, for a learning curve to show a relation between effort and outcome, a valid measure of learning is needed. Simulation-based assessments of procedural skills have robust validity evidence and are sufficiently sensitive to detect learning changes.[17]

In this study, we incorporate a mastery-based model of training a specific procedural skill – fiber optic bronchoscopy – through simulation to examine learning curves. Fiber optic bronchoscopy is a core skill in many specialties, and Virtual Reality (VR) simulators are available for training. A VR simulator is a computer-based, simulated environment in which users interact with specialized software providing visual, auditory and tactile feedback.[18] VR simulation training is advocated because of the following characteristics: similarity to real life, opportunity for self-guided learning and immediate feedback on performance with automatic scoring.[19] The VR simulator automatically scores the following clinically relevant components: duration of each procedure, number of bronchial segments reached, and number of collisions with the tracheobronchial wall. Several studies have examined the validity of these scores where VR is used alone, and have demonstrated relationship to other variables or "known-groups" validity evidence (*i.e*. the ability to discriminate among novice, intermediate and experts; and, improvement in scores with repetitive practice).[19, 20, 21] In addition, automatic scores can be combined with a raters' judgment about knowledge of the anatomy, or the ability to locate abnormal findings; these composite scores have demonstrated good internal structure and relationship to other variables validity evidence.[22, 23] VR simulation allows development of a mastery curriculum by providing unrestricted availability for trainees to practice and immediate feedback as formative assessment, with the goal of reaching a predetermined standard.

The objective of this study was to conduct a mixed-methods analysis of learning curves of novice trainees while practicing on a VR bronchoscopy simulator and to investigate patterns of growth that can reassure -or alert educators- regarding trainee performance.

2. METHODS

2.1 Study Design

To address the research questions and examine patterns of growth, we employed sequential explanatory mixed-methods strategy.[24] A combination of quantitative and qualitative methodologies should not only investigate patterns of growth, but should also explain factors that contribute to those patterns. For the quantitative methods we used descriptive statistics such as trends and growth mixture modeling. [25,26] Growth modeling is a method that can model within-person change over time, as well as changes among individuals. For the qualitative methods we used an instrumental case study design. [27,28] Case study is the study of the particularity and complexity of a case, coming to understand its activity within important circumstances. [29] This methodology allowed us to examine and explain patterns of growth and use of assessment data through in-depth study of novices involved in the simulation program.

2.2 Participant Recruitment and Setting

The study took place during October 2017 to March 2018 at the Department of Pediatric Critical Care Medicine, Hospital for Sick Children, an academic paediatric Hospital at the University of Toronto. The Research Ethics Board of the Hospital for Sick Children approved the conduct of this study. Informed written consent was obtained from each of the participants. A research assistant approached subspecialty residents in Paediatric Critical Care or Paediatric Respiratory Medicine, for whom fiber optic bronchoscopy is a core competency, and offered participation in the study. With permission of Program Directors for each subspecialty, we used part of the formal academic lectures (where all the residents are present) to explain and recruit for the study.

We approached all 25 Paediatric Critical Care subspecialty residents. 21 consented to participate in the study, and two residents withdrew early in the study because of discomfort with collection of their VR assessment data. The Paediatric Critical Care subspecialty fellows had no prior training or experience with fiber optic bronchoscopy. We approached all four Paediatric Respiratory Medicine subspecialty residents, and one consented to participate in the study (this resident had been partly included in two bedside fiber optic bronchoscopic examinations and had had no simulation training). A simulation curriculum for initial training of these residents existed and this was modified to address our questions. We also approached nine experts (pediatric critical care medicine faculty), who teach and perform this procedure frequently at the bedside; all nine experts consented; one was unable to participate because of scheduling conflicts.

2.3 Simulation Curriculum

Subspecialty trainees who are required to master bronchoscopy as a core competency, completed a simulation training as a preparation to performing the procedure under supervision at the bedside. The first part of the curriculum consisted of instructor-led group discussion to provide an overview of the procedure (consent, preparation, indication, complications), and review the major anatomic features, as well as key normal and abnormal findings. The second part of the curriculum comprised self-guided learning of the anatomy using eLearning modules. [30] The third part involved practicing the skill on a VR bronchoscopy trainer (ORSIM ®; Airway Simulation Limited, New Zealand) supervised and guided by an instructor. This supervised practice was one on one and involved two sequential studies: a warm up exercise where only the psychomotor skills needed for navigating with a bronchoscope are reviewed and practiced and the second exercise, with labeled anatomy that integrates learning anatomy together with ability to navigate the bronchoscope. Confidential, individual feedback was given by the instructor, and the time taken to complete these two supervised practices varied according to learner. This was followed by independent practice on the VR simulator. All participants were given identical instruction for the independent simulation practice, *i.e*. to reach each segmental bronchus in the entire bronchial tree, as quickly as possible, without touching the bronchial walls. During this practice, instructor was available if requested by the learner; otherwise the practice was self-guided using the feedback from the VR simulator. Learners made their own decisions whether to practice alone or with other trainees during the independent practice. Decisions about the need for additional supervised practice for trainees who seemed to have more difficulty was left to the discretion of the supervisor. At the end of the exam the VR simulator software displayed the following clinically relevant variables:

- Accuracy (*number and identity of segmental bronchi successfully entered*);
- Speed (*the time taken to complete the study*); and,
- Dexterity (*number of collisions between the bronchoscope tip and the bronchial wall*).

Participants were reassured that the scores would not be used to make any decision regarding their performance, or their opportunity to progress to supervised real-life practice. Participants were encouraged to train until their scores had plateaued, or had achieved a pre-set score ‘standard’. The chosen standard was one agreed to by eight experts, and is the published average scores of expert physicians.[19] The VR simulator was conveniently located close to the clinical practice place in order to allow participants multiple opportunities to practice.

2.4 Data Collection

Data Collection I - Quantitative Data

The automatic data from the VR simulator was available to participants after each trial and were collected and de-identified for the study purpose. Expert faculty simply tested themselves to track their learning curves with no practice in between trails. In between trials trainee participants practiced several modules or simply wanted to be involved in observational practice (other trainees or experts practicing with the VR simulator). Time used to practice in between trials was recorded from Principal Investigator (PI) (BM) who observed participants during their independent practice.

Data Collection II - Qualitative Data

The field notes were taken by the PI (BM), who was an observer during the independent simulation practice to describe strategies used by participants in between trials ***(Appendix A)***. The PI also conducted 30- minutes face-to-face semi-structured interviews with trainees in order to develop an in-depth understanding of the relationships among challenges of the task, context of training and individual choices , in producing the learning curve and also review and clarify some of the observations about strategies used during practice between trials ***(Appendix B)***. These interviews were conducted in two stages for the following reasons. First, all our participants were one case (novices practicing and getting feedback from an instructor and VR simulator toward a goal) and we wanted to interview participants right after their decision to stop simulation training and transition to bedside practice so that we had richer data and no memory recall bias. During these interviews, participants were shown their learning curves as the visual representation of learning to encourage reflection on the learning process. Second, we wanted to review the sampling and interviews after the quantitative data analysis for more in depth explanation of patterns of growth that would be indicated from the quantitative analyzes and weren't immediately available at the end of participants simulation training. Although the interview protocol (***Appendix B***) served as an initial guideline, it was modified after subsequent interviews to better capture the data and explore new themes that were identified through an iterative constant comparative analysis.

The PI also conducted a 45- minute face-to-face interview with the instructor ***(Appendix C)*** to explore their experience, strategies and assessment of multiple learners. Experts were not interviewed as they were simply trialing the simulator rather than learning from it. All interviews were audiotaped and transcribed verbatim.

2.5 Data Analysis

Data Analysis I - Quantitative Analysis

In order to generate the learning curves, the indices of performance (time, bronchial missed, collisions) were visually graphed (Y-axis) against an index of learning effort (repetitions of the bronchoscopy exams in the VR simulator; X-axis).[12] Descriptive statistics were used to examine trends. To create a composite score, eight faculty members were asked to select and rank the importance of time, bronchial segments missed and collisions. Seven out of eight faculty ranked all three equally. Combining and weighing equally the standardized scores from time, bronchial segments missed, and number of collisions, we created a standardized composite score. Mean trajectories were plotted by learner and expert groups to identify overall trends for time, bronchial missed, and number of collisions. In this context, a superior score corresponded to a lower time to complete the exam, less bronchial segments missed and less collisions. Because an overall curve, bounded by CI may not completely capture the variability of the participants because it is the range of possible average level curves, in order to represent learning curves variance we plotted overlaid individual learning curves. Growth curve analysis was used to examine patterns of growth.[25,26] This approach allows identification of different groups or patterns of learning curves (e.g., learners grouped into faster rates of growth), which have been used widely in public health and clinical research settings. [31,32],

Data Analysis II - Qualitative Analysis

The data from field notes and interview transcripts were entered into a qualitative analysis program (NVivo 10; QRS, International, Doncaster Australia) to facilitate organization and analyzes of the data. Data was initially analyzed and coded to identify themes by (BM) a Pediatric Intensivist with experience in bronchoscopy, simulation training and qualitative methods. Constant comparative analyzes of the data that enabled exploration of themes through subsequent interviews was completed by the principal and co-principal investigators (BM, MM) until a stable thematic structure was developed. [33] This structure then was then applied to the entire data set by one researcher (BM). A detailed audit trail with notes from team meetings and codes at various stages of thematic analyzes was kept.

3. RESULTS

3.1 Quantitative Data

Data from 20 (of 29) novice learners and 8 (of 9) experts recruited to the study are included. Descriptive statistics used to examine mean and standard deviation (SD) of data for each attempt (Table 1).

Mean trajectories were plotted by learner and expert groups to identify overall trends for time, bronchial segment missed, number of collisions and a standardized composite score that was created by combining standardized and weighing equally all three scores from clinically relevant variables (Figure 1).

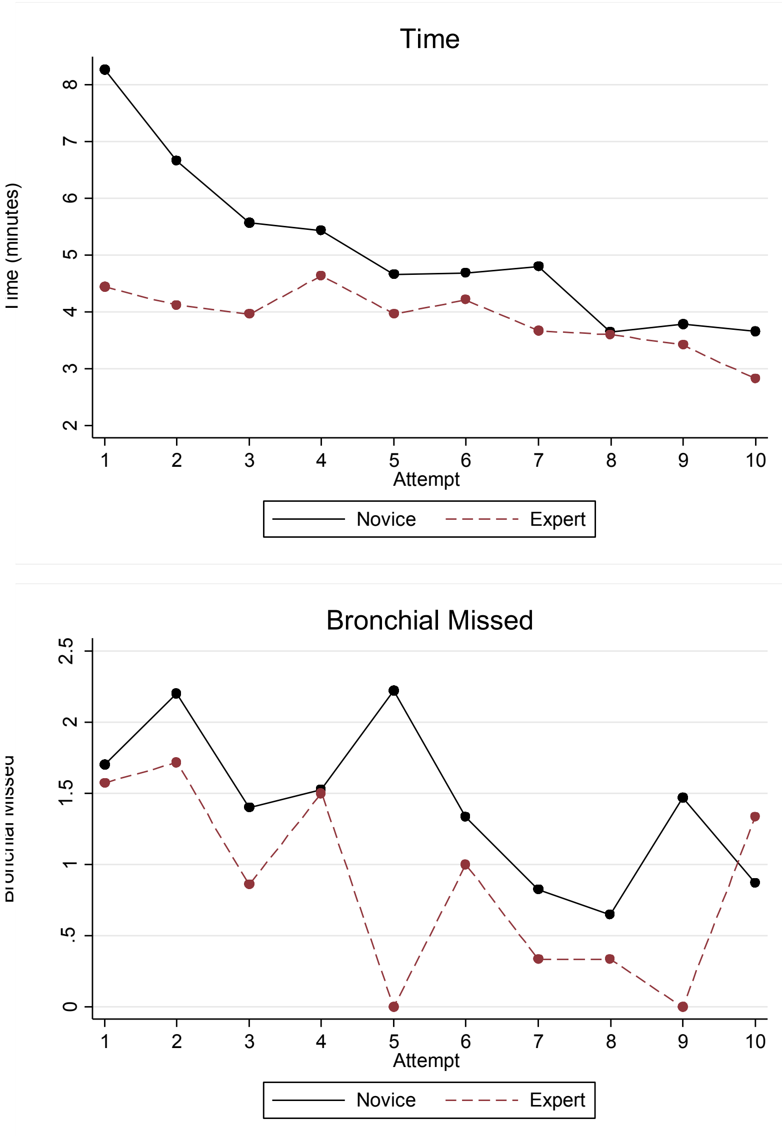
Using growth curve analysis two learner groups were statistically identified ("Learner Group A" and "Learner Group B"). Trajectories were plotted by group and compared with expert trajectories (Figure 2). In general, learner in "Group A" commenced with a lower score and plateaued at a lower score. Learners in "Group B" demonstrated a more precipitous drop in scores and, subsequently approached the expert score level.

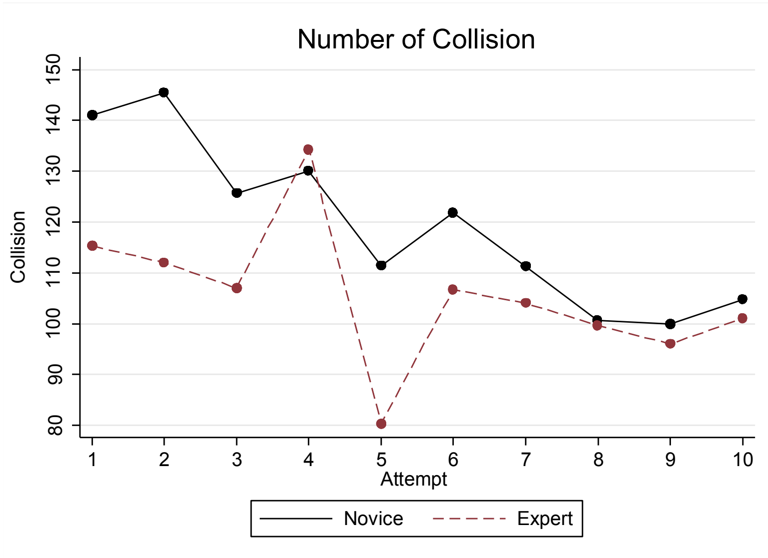
The individual learning curves for learners were contrasted with learning patterns of experts, in order to illustrate learning curve variance for both groups (see online supplement Figure 3). There were significant differences in the mean variability of scores across attempts between experts and novices for time (Mean SD = 1.25 versus 2.68) and bronchial missed (Mean SD = 1.07 versus 1.79), $P < .001$.

Table I. Descriptive Statistics: Time, Bronchial Missed, and Number of Collision

Group	Attempt	Time		Bronchial Missed		Number of Collision	
		Mean	SD	Mean	SD	Mean	SD
Expert (n = 7)	1	4.44	1.23	1.57	1.51	115.29	58.81
	2	4.12	1.43	1.71	1.38	112.00	61.41
	3	3.96	1.32	.86	1.07	107.00	56.01
	4	4.64	2.55	1.50	1.52	134.33	98.68
	5	3.97	1.36	.00	.00	80.33	7.09
	6	4.21	1.36	1.00	1.73	106.67	15.04
	7	3.67	1.04	.33	.58	104.00	34.60
	8	3.60	.87	.33	.58	99.67	5.51
	9	3.42	.77	.00	.00	96.00	4.58
	10	2.82	.60	1.33	2.31	101.00	16.09
Learner (n = 20)	1	8.27	3.17	1.70	1.78	141.00	38.64
	2	6.65	2.00	2.20	3.14	145.45	42.67
	3	5.57	2.55	1.40	1.85	125.60	36.98
	4	5.43	3.90	1.53	1.90	130.00	38.99
	5	4.66	2.96	2.22	2.26	111.44	32.73
	6	4.68	2.52	1.33	1.68	121.83	44.39
	7	4.79	3.39	.82	1.42	111.29	33.09
	8	3.64	1.55	0.65	1.17	100.59	17.79
	9	3.79	2.39	1.47	1.73	99.87	29.80
	10	3.65	2.33	.87	.99	104.67	34.91

Figure 1. **Plots of Mean Trajectories by Group: Learner and Experts**




Number of Collision
Collision
150
140
130
120
110
100
90
80
1
2
3
4
5
6
7
8
9
10
Attempt
Novice
Expert

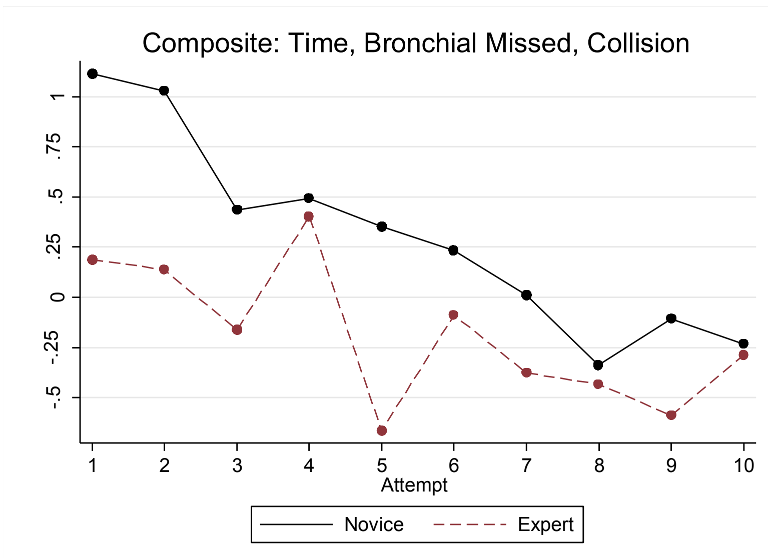
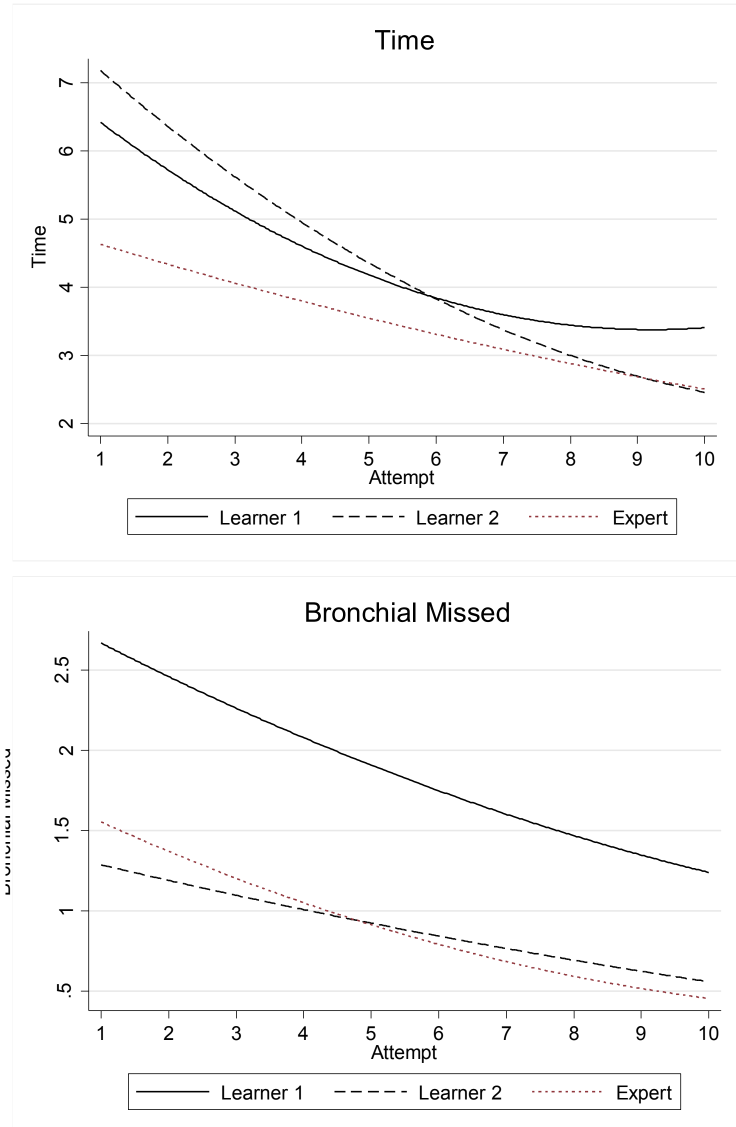
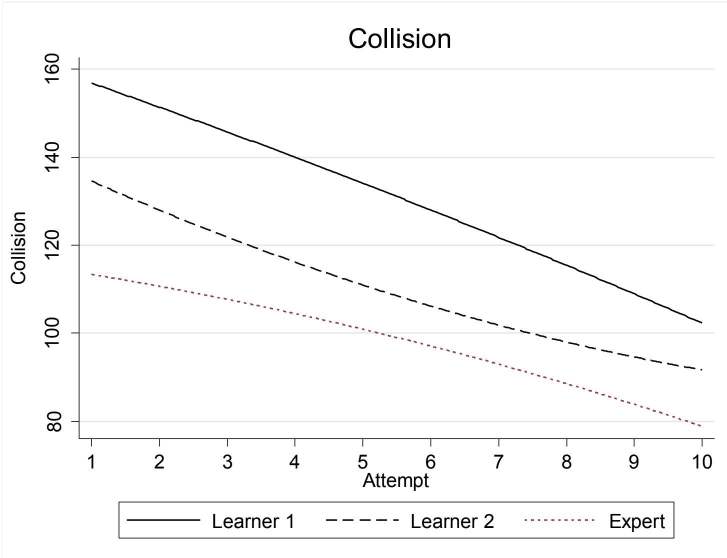
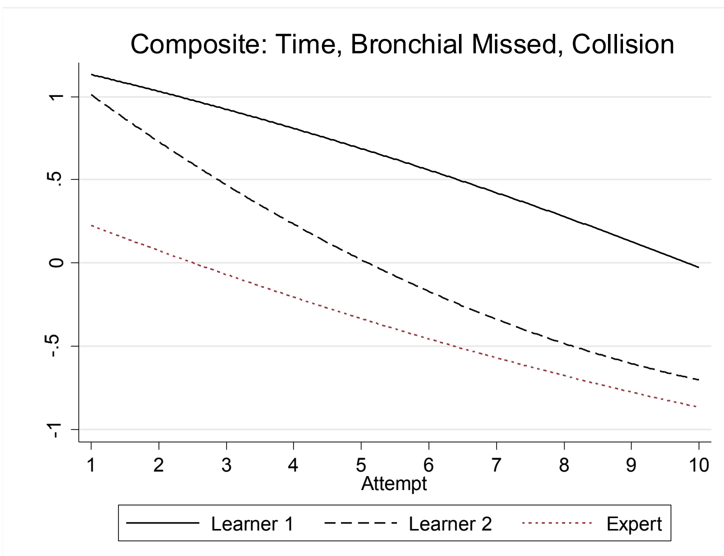

Composite: Time, Bronchial Missed, Collision
1
.75
.5
.25
0
-.25
-.5
1
2
3
4
5
6
7
8
9
10
Attempt
Novice
Expert

Figure 2. **Patterns of Trajectories by Learner Group: Projected Growth Curves**







Note: Growth Mixture Model used to estimate learner groups. Among 20 learners, 8 learners are in "Learner Group 1".

3.2 <u>Qualitative Data</u>

The qualitative analysis of observations, and the instructors' and learners' interviews, identified two groups of learners. The two groups differed according to their pattern of practice and approach to learning and using the data. Only five (of eight) learners identified as having a 'slower growth' pattern from the quantitative data were also identified as having a 'slower growth' pattern from the qualitative data. The reminder of learners (fifteen) was grouped in "Group B".

Group A

Five out of 20 learners were described as fitting in Group A (from quantitative data this group had a 'slower growth'). Group A seemed to have inherent difficulty with the task and have a mechanistic approach to practice. The approach to learning was such that simple and repetitive practice in the VR simulator would improve skills; this is in contrast to thinking about a solution or a strategy when procedural difficulties were encountered, or where performance plateaued at a low level:

> *"When you train on a simulator, you repeat always the exact same structure and then you get used it, and then you get better, but on repeating the same thing."(L20)*

> *"I didn't really change my strategy, but I think, for me, repeating it is very important thing because the more we do, the more familiar you get with the bronchoscope." (L18)*

> *"Just use it. I think the important key is just trying it again and again and again." (L16)*

> *"I can get the anatomy elsewhere, this is just for driving through airways with the scope." (L01)*

These learners also were identified from the observations as well as the interviews with the simulation instructor:

> *"If you asked me: who will need more attention, I can identify the following learners. The task is inherently more difficult for them, either the manipulation and driving of the bronchoscope in the airways or the anatomy and understanding its importance. Two of them seemed paralyzed by the difficulties and I had to come back and check on them and try to guide them through difficulties. A couple of times, with two of the learners I thought might be the way I am instructing or giving feedback and I called another colleague to take over. They generally keep doing the same thing, almost can't problem solve with or without help. Eventually they get it. They have this "aha" moment where whether what you are telling them resonates with them or through repetitive practice they find "their" solution, but it takes longer and is more random than the rest." (I)*

Group B

Twelve out of twenty learners were described as Group B (from growth models, had a faster progression and ability to reach an expert score). In fact the qualitative data identified fifteen learners whose practice was characterized by their ability to develop a deeper conceptual understanding of the task. This group of learners was able to do this through their immediate integration of knowledge of anatomy to the bronchoscopy navigation to help with spatial orientation and anticipation of movements. They also used different strategies to troubleshoot difficulties and were able to deal with the struggle by using different resources. They were also able to experiment with some solutions during the simulation and were creating variety even when task remained routine to continue motivation to practice. They kept showing curiosity and inquisitiveness about what the procedure is like in real life through discussion with experts and participating in bedside procedures when opportunities were available.

Theme 1: Integrating knowledge of anatomy with navigation of the airway

Rather than seeing the task as a simple navigation of the airway tree, these learners understood early the importance of anatomy for accurate interpretation of the finding in a bronchoscopy exam and for ease of navigation. The knowledge of the anatomy conferred on them a spatial orientation that in turn helped with the other elements of the exam such as fewer collisions and faster time to complete an exam.

> *"But I think what anatomy helped with was anticipation. So, that you know that it is here, on this side. It's like knowing your road. You know it's going to come to the right, so you go on the right lane. You know that you're going to take a right so you'll slow down, and move to the right lane. But if you don't know the road, and suddenly, the GPS has to say go take a right, then you're like, oh. So, then you're likely to be a bit bumpy. You're not crashed, but when you don't know, your car doesn't take a smooth turn. (L03)*

Theme 2: Ability to problem solve by exploiting 'struggles'

These learners saw the struggle as a moment to stop and reflect and discover new ways of performing the task.

> *"… right now it's not working out and I need to take a pause and then try again. I think that I need to pause, rethink what I need to try and that I'd want to try to improve again." (L09)*

Each of them used a variety of solution and resources to troubleshoot their difficulties. Some of them called back the instructor or recalled and used some of the previous instruction that made sense only (or more so) when they experienced the struggle:

> *"You get the instructions, but the instructions only "hit home" when you struggle at different points with your scores. When you try to figure it out, sometimes you do it on your own and discover the same thing that you were told, but didn't pay attention, because it didn't really have a meaning at that time." (L07)*

> *"So I used her feedback combined with what I was seeing on the screen and then being able to try it on my own. So she showed me for example that with my L hand on the bronchoscope is really a wrist movement, a rotational movement and so that I wanted to try it on my own to get a feel for what that movement did to the view as I was just moving my wrist." (L12)*

Other strategies used were observing and discussing different solutions with their peers or with faculty, reviewing a recording of their exam to better understand where the difficulties were, and willingness to experiment with a alternative solutions and create variety even in what might seem like a routine exercise:

> *"I asked some of the faculty participating in the study if I could watch them. I thought these people have had a lot of experience at the bedside and know what matters. I saw a few different techniques. By watching and discussing with them I figured out a few things like: tricks about remembering anatomy, how they enter the "hard to get to" bronchi, how they position themselves and what hands movements they use, what matters at bedside, how they change approaches depending on the case. Then, I experimented with some of those tricks and found the one that worked best for me and kept some others so that I have a few more tools in my "toolbox". (L14)*

> *"The exercise is routine, so you can either get frustrated doing the same thing again and again and not working or get bored. A couple of times, I practiced with other modules like upper airway and did get my navigation skills better because you have to be very steady and have full control of your movements so you twist this way, hold that alignment to get through wherever you want rather than giant spins this way and giant spins that way." (L8)*

Theme 3: Deeper understanding of the procedure and the role of simulation for preparation for bedside practice

This group of learners saw the simulator practice as preparation for bedside practice and had a deeper understanding of what the bronchoscopic procedure would be like in real life. Through discussion or observation and participation in bedside practice they had a better idea how they would apply what they had learnt in simulation, and where in real life, what they learnt in simulation would fit.

> *" … the ability to keep track of where I was, because one of the problems I think, If you want to do this (procedure) properly is that, if you say you took this sample from this segment is indeed from that segment." (L02)*

> *"In some situations they're not all important, because you just need to do something, and if it hits it hits, fine. But in other situations, when it's just a normal study, it had better be less collisions. One should not induce something. Sometimes time and collisions may be placed against each other, and you want to do something fast and you might collide, that's okay, but you need to get it fast." (L3)*

> *"I can imagine different exams need different skills and maybe all the skills, fast, going to all segments and not touching the walls." (L12)*

In summary, the qualitative data explained five of eight learners who belonged to group A with a slower growth as those who had an inherent difficulty with a task and a mechanistic versus an adaptive, flexible approach with ability to manage struggle and reach a deeper understanding to using the VR simulator practice.

4. DISCUSSION

Investigating learning curves of novices practicing with a VR bronchoscopy simulator provides insights into patterns and growth progression of learners which can have important educational consequences for both learners and educators. For learners, these individual trajectories can inform how they learn, with respect to relative or known standards of performance; for educators, patterns of learning curves provide opportunities for teaching and remediation. In this study, we identified two patterns of growth using a growth mixture model: one with a faster and one with a slower improvement. We used each learning curve as the basis of the conversation with the learner to explain these patterns of growth. We discuss our findings using two frameworks: consequences validity evidence and adaptive expertise.

The changes in medical education fueled by CBME underscore the need for valid assessment of learning. One of the frameworks to think about assessment validity is that of Messick's "the degree to which evidence and theory support the interpretations of test scores for proposed uses of tests". [34] In this framework evidence is collected from five sources: content, response process, internal structure, relationship to other variables and consequences. Decisions on learner's progression must carry the weight of the consequences of accelerating or shortening the training. Consequences evidence is rarely reported in validity studies in medical education.[35,36] We found that the growth modeling was able to identify the learners who had trouble with the skills and did not have any "false negatives" when that data was compared with teacher's reflection, learners' interview and observation of simulation practice; however, the growth model mistakenly grouped three learners that had no difficulty with a task and were progressing well as "slow growth" and as such was "false positives". This could have consequences such that more learner time and instructor time would have been dedicated to these learners when in fact it was not needed. We could imagine that the prediction errors might be even more substantial in a context other than a "simulation experiment" where the competencies might not be easy to measure or have a valid tool and the context is much more complex.

Explaining the two patterns of growth through interviews and observations, we found that even though the instruction was not specifically tailored to promote adaptation, struggle and flexibility that in fact the learners with flexible approaches, willingness to experiment with those approaches and deeper understanding of this procedure were the ones that had a faster growth. Learning is rarely a direct linear function of the effort of the learner. Learning curves constitute an indirect assessment of whether the necessary elements for learning are present for a given individual, including motivation, the degree and quality of feedback and learner's strategy to name a few. Our simulation, portraying the usual, pragmatic simulation curricula had a step-wise presentation of information, a supervised practice on the simulator and opportunities for independent practice and instructor help if needed to reach a set standard. The goal of learning is not only mastering the procedural skills in this case, but also learning how to work on a variable and changing context. [37] The complexity, inherent uncertainty and ever-changing knowledge and skills needed are common to medical practice. [38] Therefore approaches such as "preparation for future learning"[39, 40] and "adaptive expertise"[41,42] that emphasize: understanding rather than performance, struggle and risk taking and meaningful variation are relevant to medical education.

While the "slow growing" group involved themselves in repetitive practice with no explicit strategy to confront the struggle except "more practice", the "faster growing" group embraced the struggle and was able to grow by exploring diverse solutions. These students discovered these new solutions by using different resources. Our finding complement the current literature on initial struggle and "guided discovery"[43,44] but differs from it as our learners after facing the struggle were able to discover the solutions on their own.

Cognitive integration, that is, creating meaningful relationships between relevant types of knowledge, in clinical reasoning (basic science and clinical science) [45,46] and in procedural skills (how the procedure is done and why is done that way) [47] have been proven to promote acquisition and transfer of skills. Similarly, our "fast growing" group understood the importance of integrating the anatomy in the procedure for accurate interpretation of finding and better special orientation and navigation with a bronchoscope.

Moreover, these group of learners either through discussions with peers and experts or involvement in bedside procedures, had a deeper understanding about the procedure and where the simulation practice fitted in the overall training and what it prepared them for. These learners seemed well positioned for "preparation for future learning".

In essence, we are one of the first groups to provide validity evidence for "growth models" using a mixed methods, underscore the importance of an adaptive expertise approach even when learning something that is seen as a routine procedural skill and find that while immersed in a "pragmatic" simulation model that wasn't created to instruct through principles of "adaptive expertise", the majority of our learners did have an adaptive expert approach. It could be that our group of subspecialty residents that was training in a complex and unpredictable context of Intensive Care Medicine was exposed to adaptive approaches through their training and practice and that the simulation practice with their peers, experts and available instructor further promoted that approach.

In conclusion, predictive analytics while useful should be used carefully in medical education and coupled with teachers and supervisors reflection about the progress of learners. The faster growing learners not only have an inherent ease at the task but show an adaptive approach to learning by using struggle, embracing variation and forming deeper understanding. These should be encouraged in all learners.

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APPENDICES

Appendix A

Content of field notes taken during the observations of lanners practice:

Times that the learners were tested and scores.

What type of practice they were involved and for how long?

What type of problems were encountered?

What type of strategies were used for practice?

When and why did learners stop practicing?

Appendix B:

Semi-structured Participant Interview Protocol:

Duration: Flexible, 30 - 60 minutes

Setting: Private area of participant's choice

Interview structure: Semi structured; tape recorded; transcribed.

Preamble: As you have recently completed Virtual Reality Simulation training in Bronchoscopy, the purpose of this interview is to understand your experience with simulation training, your motivation for subsequent training, the effect of the automatic performance scores on your learning, your decision making to stop the simulation practice and transition to bedside with supervision and how you would guide your future learning.

Your responses will be kept confidential. You may decline to answer any question or end the interview at any time. If at any point the situation becomes stressful we can stop. We require consent so the discussion today can be audio taped. Your choice to participate or decline participation in the interview will not interfere with your access to future educational sessions or your full participation in the activities related Bronchoscopy Simulation Program.

<u>Outline for Interview:</u>

1. The interviewer will introduce themselves and thank the participant for their time, interest and for sharing their experience regarding the bronchoscopy simulation training they have just completed.

2. The pre-amble will be reviewed (see below). Consent for audiotaping the interview will be obtained if it has not already been completed at the time of recruitment.
3. The participant will be invited to ask any questions or raise any concerns they may have before starting.
4. The interviewer will restate that they may refrain from answering at anytime or may remove themselves from the discussion at any point without judgment or penalty.
5. The interview will then proceed based on the sample question guide below.
6. The interview will end the interviewer thanking the participant for their time, and take any other questions they may have.

Sample questions for the interview:

Is this skill important to you? Is this a skill you want to be "good enough", competent or outstanding? (perceived value of the skill)

You have stopped your VR simulation training and want to transition to bedside with supervision? How did you make this decision?

You were given a score to work toward. Did you reach that performance? Why?

What was your motivation to practice?

What would make you continue training in VR? Prompts - Better simulator fidelity, scheduling, reward system, continued guidance and supervision?

Do you think you are competent in this procedure now? Did you finish when you thought you were competent?

In your independent practice, how did you use the automatic score of VR?

What was the effect of seeing the rate of your learning (automatic scores displayed to you at end of each exam)? What was your perception of challenges?

What were your strategies to overcome challenges?

If you are alone and a bronchoscopy is needed, would you perform it without supervision? Do you think if you practiced more in VR you would feel more confident at bedside? Why?

What is your goal when you practiced in VR?

Do you think this simulation practice is going to help you get better?

When you were practicing, did you want to improve your score, did you want to compete with your other trainee's scores?

How will you continue your further learning in this skill? What will you do? What resources will you use?

After the VR training what are you looking to learn from new experiences?

Have you seen a bedside bronchoscopy procedure performed by faculty? What is your performance compared to them?

What are some of the challenges you would encounter at bedside you think? How would you solve them? How can you modify the environment (resources, people) to help your performance? If things don't work out for you at bedside how will you revise? Would you ask for help? Would you ask for other people's opinion?

What does it mean to be successful/ expert in this skill? Do you feel accomplished, expert?

Appendix C:

Sample interview for the simulation instructor

Can you identify any learners who had difficulty with the skill?

Who are they?

Why did you select these learners? What do they have in common?

Were you called from these learners and other learners?

Why were you called?

What instructions or help did you give?

Can you identify group of leaners that are similar? How many groups? What are the identifiers for each group?

Would you change the curriculum? How would you change the curriculum now?

VITA

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Biographical Information

Primary Office	The Hospital for Sick Children 555 University Ave Toronto, Ontario, Canada M5G 1X8
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EDUCATION

Degrees

2013 Jul – present	MHPE (Masters of Health Professions Education - Medical Education) *University of Illinois at Chicago, Chicago, Illinois, USA*
1991 Sep - 1997 Aug	MD (Doctor of Medicine) *Faculty of Medicine, University of Tiranë, Tirana, Albania*

Postgraduate, Research and Specialty Training

2010 Sep - 2012 Jun	Education Scholars Program *Centre for Faculty Development, Faculty of Medicine, University of Toronto, Canada*
2008 Jul - 2010 Jun	Postgraduate Medical Trainee, *Paediatric Critical Care Medicine, Hospital for Sick Children & University of Toronto, Canada*
2005 Jul - 2008 Jun	Postgraduate medical trainee, *Department of Paediatrics, Hospital for Sick Children & University of Toronto, Canada*
2004 May - 2005 May	International Medical Graduate

	Ontario International Medical Graduate Program, University of Toronto, Canada
1998 Jan - 1999 May	Postgraduate Medical Trainee,
	Department of Dermatology, University of Tiranë, Tiranë, Albania

Qualifications, Certifications and Licenses

2011 Jun	Subspecialty - Critical Care Medicine
	Fellow of the Royal College of Physicians and Surgeons of Canada
2009 Jun	Specialty - Paediatrics
	Fellow of the Royal College of Physicians and Surgeons of Canada
2005 Jul	License (#83268),
	College of Physicians and Surgeons of Ontario, Canada
2003 Sep	Licentiate
	Medical Council of Canada

EMPLOYMENT

Current Appointments

2018 Jul - present	Associate Professor of Paediatrics - *University of Toronto*
2010 Jul - present	Staff Physician - *Department of Critical Care, The Hospital for Sick Children*
2010 Jul – present	Project Investigator - *Research Institute, The Hospital for Sick Children*

Previous Appointments

2011 Jul - 2018 Jul	Assistant Professor of Paediatrics - *University of Toronto*
2010 Jul - 2011 Jul	Lecturer in Pediatrics - *University of Toronto*

HONOURS AND CAREER AWARDS

Teaching and Education Awards

NATIONAL

2012 - 2014	**Royal College Fellowship for Studies in Medical Education** *From the Royal College of Physician and Surgeons of Canada - competitive award for promising candidates to*

acquire specialist knowledge in medical education (2-3 awards per year).
$45,000 (***Principal Investigator***)

LOCAL

2017 - 2018 **University of Toronto Critical Care Teaching Award (SickKids)**

Interdepartmental Division Of Critical Care Medicine, Faculty of Medicine, University of Toronto to the staff member voted by the trainees in their hospital department as the outstanding teacher of that year.

2012 - 2014 **POWER Teaching Award**

Postgraduate Medical Education, Department of Paediatrics, Faculty of Medicine, University of Toronto (Postgraduate MD, Core Program) to the faculty with the highest POWER teaching evaluation scores over a period of two years as evidence of sustained excellence in teaching for Paediatric Residents.

2011 - 2012 **Harry Bain Award**

Postgraduate Medical Education, Department of Paediatrics, The Hospital for Sick Children (Postgraduate MD, Residents) to the full-time member of the Hospital voted by the residents as the outstanding teacher [I am the only paediatrician to have received this award in their first year of appointment].

2009 - 2010 **The John F. Edmonds Teaching Award**,

Department of Critical Care Medicine, The Hospital for Sick Children (Graduate Education, Rotation and Elective Trainees) to the Fellow who voted as the best teacher that year by the rotating and elective trainees.

2007 - 2008 **Christopher Ondaatje Award**

Postgraduate Medical Education, Department of Paediatrics, The Hospital for Sick Children (*Undergraduate MD*) *for excellence in teaching by a resident in paediatrics.*

GRANTS, CONTRACTS AND CLINICAL TRIALS

PEER-REVIEWED GRANTS

FUNDED

Grants

2016 – 2017 InCURS: Intensive Care Units Residents Scheduling Study
Canadian Institutes of Health Research (Project Grant)
$100,000 (Collaborator; PI: CS Parshuram)

2016 - 2017 **Programmatic Assessment in the Workplace: A Realist Exploration Of Contexts, Mechanisms, and Outcomes in Critical Care Medicine**
Royal College of Physician and Surgeons of Canada.
$55,000.00 (Co-Investigator; PI: D. Piquette)

2016 - 2017 Organ and Tissue Donation Competency Based Medical Educational Program For Ontario Critical Care Medical Residents.
Trillium Gift of Life Network
$99,000.00 (Co-Investigator; PI: A. Sarthee)

2015 – 2017 In search of the optimal bronchoscopy training platform: Evaluating the use of a novel, low cost, virtual tool for pre-training novice learners.
Perioperative Services Innovation Projects, Hospital for Sick Children.
$9,000 (Principal Investigator)

2014 – 2015 Rehearsal vs. Premiere: Chest tube skills from simulation to bedside.
Pediatric Consultant's Education Research Grant, Hospital for Sick Children.
$ 5,000 (Principal Investigator)

2013 – 2014 U/S guided central lines: transfer of skills from simulation to bedside.
Pediatric Consultant's Innovation Development Grant, Hospital for Sick Children.
$2,900 (Principal Investigator)

2013 – 2014 RESPECT: a tool to improve patient care quality and safety and facilitate team learning
Canadian Institutes of Health Research (Catalyst Grant)
$92,205 (Co-Investigator; PI: C. Parshuram)

2012 - 2014 Fellowship for Studies in Medical Education.
Royal College of Physician and Surgeons of Canada.
$45,000.00 (Principal Investigator)

PEER-REVIEWED PUBLICATIONS

Journal Articles

1. Sarti AJ, Sutherland S, Healey A, Dhanani S, Hartwick M, Oczkowski S, Messenger D, Soliman K, Ball I, **Mema B**, Cardinal MP, Valiani S, Cardinal P. A multicenter investigation of organ and tissue donation education for critical care trainees. ***Canadian Journal of Anesthesia***. In Press 2018 (**C**)

2. Taylor KL, Parshuram CS, Ferri S, **Mema B**. A description of the "event manager" role in resuscitations: A qualitative study of interview and focus groups of resuscitation participants. ***Journal of Critical Care*** 39: 254-258, 2017 (**SA**)

3. **Mema B**, Park YS, Kotsakis A. Validity and Feasibility Evidence of Objective Structured Clinical Examination to Assess Competencies of Pediatric Critical Care Trainees. ***Critical Care Medicine*** 44: 948-53, 2016 (**PA**).

4. **Mema B**, Harris I. The Barriers and Facilitators to Transfer of Ultrasound-Guided Central Venous Line Skills From Simulation to Practice: Exploring Perceptions of Learners and Supervisors. ***Teaching Learning Medicine*** 28:115-24, 2016 (**PA**)

5. Ma IW, Pugh D, **Mema B**, Brindle ME, Cooke L, Stromer JN. Use of an error-focused checklist to identify incompetence in lumbar puncture performances. ***Medical Education*** 49: 1004-15, 2015 (**C**)

6. Knox ADC, Reddy S, **Mema B**, DeMoya M, Cili-Turner E, Harris I. "Back in the Day"… What are Surgeon Bloggers Saying About Their Careers? ***Journal of Surgical Education*** 71: 21-31, 2014 (**C**)

Book Chapters

1. **Mema, B.** and Bagli, D. Chapter: Urology. The Hospital for Sick Children Manual of Pediatrics. 11th ed., The Hospital for Sick Children Manual of Pediatrics. Toronto: Elsevier. (2008). (**PA)**

PRESENTATIONS AND SPECIAL LECTURES

INTERNATIONAL

September 2018: International Conference on Residency Education 2018 (ICRE), Halifax

- *Workshop:* Simulation for training and assessment in CBME (**B. Mema**, A. Kawamura, D. Piquette) **(Co- PA)**
- *Workshop:* Data Informed learning: helping trainees use of their assessment data (**B. Mema**, D. Piquette, A. Kawamura) **(Co- PA)**

- *Presentation:* National assessment of individual within a team context: feasibility, validity, its role in CBME and future directions **(B. Mema**, E. Gilfoyle) **(PA)**

August 2018: An International Association for Medical Education 2018 (AMEE), Basel

- *Point of view:* Mastery learning in simulation before transition to bedside: are there drawbacks? (B. Willi, **B. Mema**) **(SA)**

June 2018: Society in Europe for Simulation Applied to Medicine 2018 (SESAM), Bilbao

- *Workshop:* Validity of assessment tools in Simulation **(B. Mema**)
- *Workshop:* Multimedia in Simulation: using it in light of how brain works **(B. Mema**, L. Rodriguez) **(PA)**

May 2018: International Pediatric Simulation Society 2018 (IPSSW), Amsterdam

- *Workshop:* National assessment of individual within a team context: feasibility, validity, its role in CBME and future directions **(B. Mema**, E. Gilfoyle) **(PA)**
- *Workshop:* Virtual reality simulator for skills training: using them to the max **(B. Mema**, E. Gilfoyle) **(PA)**
- *Presentation:* Simulation for training and assessment in CBME **(B. Mema)**

March 2018: International Medical Conference (ICME) & Ottawa Conference, Abu Dhabi

- *Workshop:* Multimedia: using it in light of how human brain works (**B. Mema**)

January 2018: International Medical Simulation in Healthcare (IMSH), Los Angeles

- *Workshop:* Virtual Reality Simulators for skill training: using them to the max (**B. Mema**, A Kawamura) **(PA)**
- *Workshop:* Assessment tools in Simulation: develop one? (**B. Mema**, A Kawamura) **(PA)**
- *Presentation for Faculty development:* Simulation for learning and assessment in CBME: using it wisely (**B. Mema)**

February 2017: International Medical Simulation in Healthcare (IMSH), Orlando

- *Workshop:* Procedural teaching: beyond see one, do one (**B. Mema**, MA Moga) **(PA)**

December 2016: Johns Hopkins Pediatric Critical Care Boot Camp, Baltimore

- *Invited Simulation scenario facilitator:* Lung US, Donation after Cardiac Death, Difficult Airways, Managing high ICP

September 2016: International Conference on Residency Education (ICRE), Niagara Falls

- *Workshop:* "Assessing Competence: is there a valid tool or do I have to develop one?" (**B. Mema**, A. Kawamura) **(Co- PA)**

June 2016: World Congress Pediatric Intensive Critical Care 2016, Toronto

- *Invited Presentation:* How to secure and maintain CVL access in the PICU
- *Organizer and Facilitator* World's trainee's day "Simulation Boot Camp"
- *Co- organized* "Education Symposium"
- *Invited Workshop:* Multimedia: using it in light of how human brain works **(B. Mema**, A. Kawamura) **(PA)**

May 2016: International Pediatric Simulation Society 2016 (IPSSW), Glasgow

- *Workshop:* Validity of Simulation Based Assessment Tools **(B. Mema**, A. Kawamura) **(Co-PA)**

May 2016: International Pediatric Simulation Society 2016 (IPSSW), Glasgow

- *Presentation:* Effective use of Simulation for Procedural Teaching in Medical Education

April 2016: University Hospital of West Indies: Department of Anesthesia and Intensive Care, Kingston, Jamaica

(Invited Lecturer to help with creating a Paediatrics curriculum within the Adult Critical Care Training)

- *Lecture:* Mechanical ventilation
- *Lecture:* Diabetic Ketoacidosis
- *Lecture:* Severe Asthma
- *Lecture:* Acute respiratory distress syndrome
- *Lecture:* Fluid and Electrolyte Management
- *Lecture:* Brain Death
- *Lecture:* Movements in brain death

October 2015: International Conference on Residency Education (ICRE), Vancouver

- *Workshop* "Develop a simulation based objective standardized clinical exam (OSCE) in a competency based medical education (CBME) era." **(B. Mema**, A. Kawamura) **(Co-PA)**

February 2015: Nagoya University, Nagoya, Japan

- *Invited Presentation:* Building Technical Skills Curricula based on Motor Learning theories
- *Invited Presentation:* Life at Sick Kids: Clinical service and education

February 2015: 3rd International Faculty Development Conference (IFDC), Singapore

- *Invited Presentation:* "Procedural Teaching in Medical Education: Beyond see one, do one …"
- *Workshop:* "Develop a simulation based objective standardized clinical exam (OSCE) in a competency based medical education (CBME) era." (**B. Mema**, A. Kawamura) **(Co-PA)**
- *Workshop:* "Feedback: Through the looking glass" (**B. Mema**, A. Kawamura) **(Co-PA)**

February 2015: National University Hospital Singapore

- Invited to give a special workshop for Advanced Practice Nurses (APN) developing a high stakes licensing exam "Validity of OSCE for high stake decisions" **(B. Mema**, A. Kawamura) **(Co-PA)**

October 2014: First Pediatric Acute Care Course for Emergency Medicine and PICU Physicians, Yerevan, Armenia

(Invited to participate in the Program Organizing Committee and facilitate lecture, workshops and simulation scenarios)

- *Lecture:* Cardiac Emergencies in Pediatrics
- *Lecture:* AHA updates
- *Lecture:* Respiratory Emergencies in Pediatrics
- *Lecture:* Physiology of Shock
- *Lecture:* Septic shock: from physiology to management
- *Workshop:* Advanced Pediatric skills: Intubation, IO and chest tube placement
- *Simulation scenarios:* Arrhythmia management
- *Simulation scenarios:* Tension Pneumothorax
- *Simulation scenarios:* Respiratory arrest

October 2013: Pediatric Intensive Care Rounds, Hamad Medical Corp., Doha, Qatar

- *Invited Presentation:* Crisis resource management principles

July 2013: The 14th Annual MHPE Summer Conference, Department of Medial Education, College of Medicine/University of Illinois at Chicago

- *Invited Presentation:* In pursuit of optimal simulation training: Initial experiences with ultrasound guided line insertion

October 2012: Pediatric Intensive Care Rounds, Hamad Medical Corp., Doha, Qatar

- *Invited Presentation:* Teaching technical skills

August 2012: Department of Medial Education, College of Medicine/University of Illinois at Chicago

- *Invited Workshop:* Learner in difficulty (B. Sandefeur, **B. Mema**, A. Corcoran, E. Bassilious) **(Co-PA)**

September 2011: Neonatal Intensive Care Rounds, Hamad Medical Corp., Doha, Qatar

- *Invited Presentation:* Teaching technical skills through simulation
- *Invited Presentation:* Surviving Sepsis: The good, the bad and the ugly

November 2011: National Conference of Pediatric Critical Care, Hyderabad, India

- *Invited Presentation:* Simulation as a learning tool in PICU
- *Invited Presentation:* Training the Pediatric Intensivist
- *Invited Presentation:* Catheter Related Blood Stream Infections
- Full day Workshop on Simulation of Pediatric emergencies
  (Organizing committee and Faculty - scenario developer and facilitator)
- Procedural Workshop:
  (Organizing Committee and Faculty)

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September 2018: Simulation Summit 2018 RCPSC, Ottawa

- *Workshop:* Data informed learning: helping trainees make sense of their simulation assessments **(B. Mema**, D. Piquette, A. Kawamura) **(Co-PA)**

May 2018: Canadian Conference Medical Education, Halifax

- *Workshop:* Simulation for learning and assessment in CBME: using it wisely (**B. Mema**, D. Piquette, A. Kawamura, M. Mylopoulos) **(PA)**

December 2017: SIMOne (Simulation Network) and CSN (Canadian Simulation Network) expo 2017, Toronto

- *Workshop:* "Assessing Competence: is there a valid tool or do I have to develop one?" **(B. Mema**, A. Kawamura) **(Co-PA)**
- *Workshop:* Virtual Reality Simulators for skill training: using them to the max (**B. Mema**, A Kawamura, D. Piquette) **(PA)**
- *Invited - Simulation in action:* Demonstrating building a simulation model, targeting mental representations in bronchoscopy skills **(PA)**
- *Poster and oral presentation judge*

September 2017: Canadian Critical Care Forum 2017 (CCCF), Toronto

- *Presentation:* Rehearsal vs. Premiere: transfer of skills from simulation to bedside (**B. Mema**)

May 2017: Canadian Conference Medical Education, Winnipeg

- *Workshop:* WORKPLACE BASED ASSESSMENT in CBME (D. Piquette, **B. Mema**, C. Lee) **(Co-PA)**

October 2016: Simulation Summit RCPSC, St Johns, NLFD

- *Workshop:* "Assessing Competence: is there a valid tool or do I have to develop one?" **(B. Mema**, A. Kawamura) **(Co-PA)**
- *Award Judge* (Briseida Mema)

December 2015: SIMOne (Simulation Network) expo 2015, Toronto

- *Workshop:* Effective use of simulation for procedural teaching in medical education: beyond..."see one", "do one"..."kill one" (**B. Mema**, A. Kawamura) **(Co-PA)**

December 2015: SIMOne (Simulation Network) expo 2015, Toronto

- *Workshop:* "Multimedia in simulation: building it in light of how human mind works." **(B. Mema**, S. Dev) **(Co-PA)**

November 2015: Simulation Summit RCPSC, Banff

- *Workshop:* "Validity of simulation-based assessment tools" **(B. Mema**, A. Kawamura) **(Co-PA)**

November 2015: Simulation Summit RCPSC, Banff

- *Workshop:* "Effective use of simulation for procedural teaching" **(B. Mema**, A. Kawamura, V. Chin) **(Co-PA)**

December 2015: SIMOne (Simulation Network) expo 2015, Toronto

- *Invited - Simulation in action:* Demonstrating the building of the chest tube model and its training uses with hybrid simulation (HiFi and SP) **(PA)**

December 2015: SIMOne (Simulation Network) expo 2015, Toronto

- *Workshop:* "Validity of Simulation based assessment" **(B. Mema**, A. Kotsakis) **(Co-PA)**

September 2012: 9th Annual Pediatric Emergency Medicine Conference, Toronto

- *Invited Facilitator*: Procedural workshop "*CVL and Thoracocentesis"*