The American Journal of Surgery (2016) 212, 475-484

The American Journal of Surgery

Clinical Science

A hierarchical task analysis of cricothyroidotomy procedure for a virtual airway skills trainer simulator

Doga Demirel, B.Sc.[a], Kathryn L. Butler, M.D.[b], Tansel Halic, Ph.D.[a,*], Ganesh Sankaranarayanan, Ph.D.[c], David Spindler, M.Sc.[d], Caroline Cao, Ph.D.[d], Emil Petrusa, Ph.D.[b], Marcos Molina, Ph.D.[e], Daniel B. Jones, M.D.[e], Suvranu De, Ph.D.[c], Marc A. deMoya, M.D.[b]

[a]Computer Science Department, University of Central Arkansas, 201 Donaghey Avenue, Conway, AR, 72035, USA; [b]Department of Surgery, Massachusetts General Hospital, Harvard School of Medicine, Boston, MA, USA; [c]Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA; [d]Department of Biomedical, Industrial, and Human Factors Engineering, Wright State University, Dayton, OH, USA; [e]Department of Surgery, Beth Israel Deaconess Medical Center, Harvard School of Medicine, Boston, MA, USA

KEYWORDS:
Surgical education;
Surgical simulator;
Cricothyroidotomy;
Cricothyroidotomy simulator

Abstract

BACKGROUND: Despite the critical importance of cricothyroidotomy (CCT) for patient in extremis, clinical experience with CCT is infrequent, and current training tools are inadequate. The long-term goal is to develop a virtual airway skills trainer that requires a thorough task analysis to determine the critical procedural steps, learning metrics, and parameters for assessment.

METHODS: Hierarchical task analysis is performed to describe major tasks and subtasks for CCT. A rubric for performance scoring for each task was derived, and possible operative errors were identified.

RESULTS: Time series analyses for 7 CCT videos were performed with 3 different observers. According to Pearson's correlation tests, 3 of the 7 major tasks had a strong correlation between their task times and performance scores.

CONCLUSIONS: The task analysis forms the core of a proposed virtual CCT simulator, and highlights links between performance time and accuracy when teaching individual surgical steps of the procedure.

The first priority in the management of critically ill patients is establishment of a secure airway to ensure oxygenation and ventilation. Airway compromise represents a leading cause of preventable death in trauma patients, affects all populations, and delivers devastating consequences when not immediately rectified.[1] When challenging anatomy precludes intubation by conventional

The authors declare no conflicts of interest.

* Corresponding author. Tel.: +1-501-852-8280; fax: +1-501-450-5615.

E-mail address: tanselh@uca.edu

Manuscript received February 4, 2015; revised manuscript July 27, 2015

http://dx.doi.org/10.1016/j.amjsurg.2015.08.029

means, an emergency surgical cricothyroidotomy (CCT) is a life-saving maneuver, and often the only viable option.[2,3]

Despite the life-saving role of this procedure, only 1% of all critical airways require CCT, limiting trainee experience. The Accreditation Council for Graduate Medical Education recommends that critical care fellows perform at least 3 CCT procedures during their training years to develop proficiency[4]; however, emergency medicine physicians have a sufficiently high success rate for intubation (97% on fewer than 2 attempts) that opportunities to fulfill this quota are few.[5] This infrequency creates a dilemma, as the vital role of CCT in life-threatening scenarios mandates a strict knowledge of anatomic landmarks and a high level of surgical dexterity. Indeed, CCT can incur a high complication rate, varying from 6% to 40%.[2,6] Complications include laceration to nearby structures, vocal cord damage, vascular injury, and creation of a false lumen, all which compromise the airway and increase mortality.[6]

Proficiency in CCT requires training supplemental to clinical experience, to equip practitioners with the skills to safely manage these high-stakes situations. The American College of Surgeons has attempted to bridge this training gap through *Advanced Trauma Life Support*[7]; however, this course offers practice on a sporadic basis, without a graded continuum of training. Moreover, low-fidelity simulators used in courses such as *Advanced Trauma Life Support* are costly and plastic mannequins lack of the realistic tactile feedback optimal for mastering this surgical procedure.[4,8,9] Concurrently, porcine and human cadavers, although more realistic, are impractical, as the CCT membrane becomes damaged with only one use.[10] Few models offer practice with procedural complications or anatomic variants.

In contrast to the aforementioned simulators, virtual reality (VR) simulators offer a risk-free training and assessment platform at various difficulty levels. VR simulators allow the trainers to repeatedly perform tasks and to receive quantitative feedback on their performance.[9,11] These qualities allow for improved operating room and emergency room performances.[12–15]

The long-term aim of our study is the development of a VR simulator for emergency CCT, with an emphasis on replication of tactile sensation and a realistic sense of proprioception using haptics technology. We seek to incorporate the multiple complex variables–cognitive and mechanical–involved in the successful performance of this life-saving procedure, to create a high-fidelity simulator ideal for systematic training. Our ultimate goal is to integrate clinical practice with technology into an elegant teaching tool, and to equip trainees with the proficiency and confidence that their patients require in the direst of circumstances. Toward this end, we performed a hierarchical task analysis (HTA) of the CCT procedure, to identify key metrics of performance and assessment for use in the CCT simulator.

Methods

Procedure analysis

A HTA is a structured and objective approach to identify and describe the procedural steps taken to achieve goals. HTA decomposes the procedure into a hierarchy of tasks and subtasks and expresses the relations among these tasks. The goal of this hierarchical expression is to objectively detail each and every step to formulate necessary or optional actions and decisions performed during the surgery. The derivation of HTA is necessary for the development of performance metrics and subsequently in depth time and performance analysis. In HTA for CCT, a total of 7 videos of experts performing procedure were recorded. One CCT was performed on a hospitalized patient in an emergent setting, and 6 CCT procedures were performed on cadavers in the Advanced Surgical Skills for Exposure in Trauma course. Each cadaver-based procedure was recorded with 3 Go Pro cameras from different angles. Two of the 3 cameras were situated for capturing observer views (as seen in Fig. 1), and 1 camera was attached to the surgeon's head to capture a first person view. All recorded videos were deidentified to remove any cadaver or surgeon-specific data before analysis. For completeness of the video analysis, the procedure and the tasks analysis are discussed in the following.

Five distinct steps comprised the task analysis: (1) initiation of procedure, (2) creating incision, (3) securing airway, (4) verification, and (5) suturing. Each main task had several subtasks. The list of the main tasks with their start and end time events for video analysis is listed in Table 1. The hierarchy of these tasks, their order of execution, and their relation are shown in Fig. 2.

In all cases, the preparation of instruments task was already completed before the recording of the video. Furthermore, although verification of the endotracheal tube (ETT) is always a required step to identify the successful oxygenation of the patient, we could not include this task in our measurements as all except 1 procedure were performed on cadavers. For these reasons, the verification and preparation tasks were removed

Figure 1 Observer camera view.

Table 1 Descriptions of start and end times based on the hierarchical task tree

Task (CCT)	Start time event	End time event
Preparation	Collect necessary instruments	All instruments collected
Identification of landmarks	Palpating the thyroid cartilage	Thyroid cartilage, cricoid cartilage, and cricothyroid membrane locations identified
Incision	Start incision with scalpel	Finger or clamp placed into cricothyroidotomy
Dilate CCT	Insertion of dilator	Insertion of ETT
Hook CCT	Insertion of hook	Insertion of ETT
Insertion of ETT	Inserting tube into the incision	Airway connected to breathing circuit
Verification of ETT	Inspection of airway	Verbal confirmation of airway in correct location, visualization of proper CO2 reading from capnography, or auscultation of bilateral breath sounds
Securing ETT	Tube connected to ventilator circuit or bag mask	Tube sutured to the patient

CCT = cricothyroidotomy; ETT = endotracheal tube.

from the time analysis, and are denoted as italicized tasks with ellipsoid borders in the task tree in Fig. 2.

The CCT procedure starts with the equipment preparation. The necessary equipment includes; #10 or #11 scalpel to create an incision. Kelly clamp, finger, or a trousseau dilator can be used to dilate the CCT. A 6-mm ETT is used to secure the airway in the absence of a flanged tracheostomy and ventilate the patient. Next step following the preparation of the instruments is the identification of surgical landmarks. This requires setting the patient in supine position with hyperextending the neck. This improves the physicians' ability to palpate the thyroid cartilage and locate the cricothyroid membrane located between the thyroid and cricoid cartilage. The surgeon needs to palpate from the sternal notch to identify the cricoid cartilage to confirm the landmarks. This task is easier in male patient or male cadaver because of the larger thyroid and cricoid cartilages. During the incision task, a 4 to 5-cm midline horizontal or preferably a vertical incision is made over the cricothyroid membrane.[16] The thyroid gland is highly vascular and avoided by making an incision directly over the cricothyroid membrane.[17] Because of the fact that blood and soft tissue shifting will quickly obscure landmarks, a finger, Kelly clamp, a tracheal hook, or a tracheal dilator is promptly placed through the incision into the airway. The use of tracheal hook helps to pull the thyroid cartilage of the way during the insertion of ETT and provide traction; however, the tracheal hook is optional. Dilation with or without the use of tracheal hook tasks must be completed before ETT placement. In ETT placement, a 6.0-mm ETT is inserted and advanced far enough to ensure that the cuff is in the trachea.[18] If a

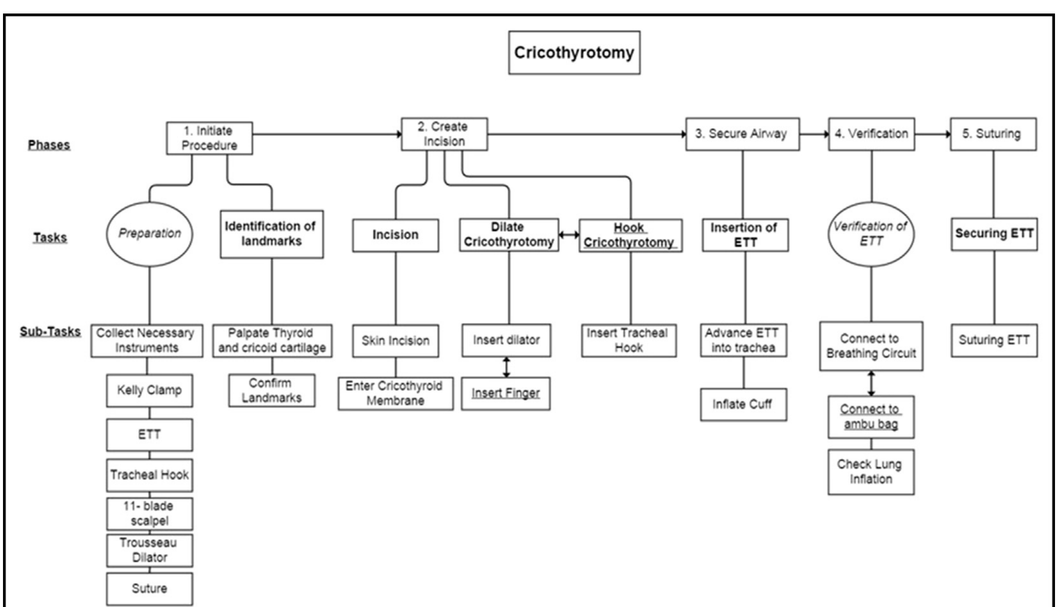

Figure 2 Hierarchical decomposition tree for CCT phases. Forward arrows in the tree indicate a linear progression to the next step, and double-headed arrows with underlined text indicate that either of steps can be performed. Only main tasks with bold text are used for video analysis. The correctness of this hierarchical task tree has been validated by expert surgeons with multiple iterations.

Table 2 Operative errors and possible occurrence phases for CCT procedure

Phase	Errors and mistakes	Occurrence and Complications
Initiate procedure phase	Fail to locate (FL) correct incision landmarks	• Caused due to misidentification of thyroid cartilage, cricoid cartilage, cricothyroid membrane.
	Thyrohyoid membrane (TM) incision	• Caused due to failed identification of the landmarks • Labeling thyrohyoid membrane as the cricothyroid membrane. • Cutting the thyroid causing major bleeding
Create incision phase	Failed incision (FI)	• Caused due to wrong incision direction, wrong incision size, and wrong location incision. • Includes multiple incisions.
	Cutting the anterior jugular veins (CJV)	• Caused due to incision at wrong location or transverse as opposed to midline incision.
	Fracture of cricoid or thyroid cartilage (FC)	• Caused due to rough handling of tracheal hook while hook CCT.
	Excessive bleeding/hematoma (EB)	• Caused due to blade carried too deep while creating the incision. • Caused due to thyrohyoid membrane incision
	Tracheal injury (TI)	• Caused due to incision is too deep and excessive force is exerted. • Failure to remove tools before performing tasks (if used) or excessive ETT cuff inflating or removing the dilator and ETT at the same time.
Secure airway phase	False passage (FP)	• Caused due to loss of tract while securing the airway.
	Retrograde placement(RP)	• Caused due to tube angled upward while securing the airway.
	R main stem placement (MP)	• Caused due to inserting the ETT too deep while securing the airway.
	Loss of tube (LT)	• Caused due to losing the manual control of ETT.
	Incorrect air pressure (IAP) for the ETT cuff.	• While not deadly immediately, too much pressure can cause leak around the tube. • Complications can include tissue damage.
Verification phase	Failure to validate or check successful intubation (FV).	• Caused due to failure to visualize the lungs (chest) moving, auscultate the lungs and stomach or to check oxygenation levels and CO2 is being expelled from ETT (capnography).
	Failure to secure the ETT (FST)	• Caused due to ETT being not secured properly or ETT being moved while suturing.
Entire procedure	Lack of oxygen (LO)	• Caused due to procedure not being completed in within the frame. • Patient not preoxygenated (if appropriate)
	Fail to intubate (FTI)	• Caused due to intubation not being completed within the time frame or too much tissue damage/collisions. • Failing to detect incorrect intubation or unacceptable oxygen levels for a specified time.
	Other injuries (OtI)	• Injuries, in areas that are not directly involved in the procedure, such as; esophageal damage, or cuts in irrelevant places or hypopharyngeal laceration during CCT • Also can be caused due to the poor execution.

CCT = cricothyroidotomy.

Table 3 Learning objectives mapping of CCT tasks

Task number	Tasks	Learning objectives: 1. Identify the key landmarks for performing a CCT	2. Perform an appropriate skin incision	3. Enter the cricothyroid membrane	4. Dilate the CCT with finger or with clamp	5. Insert a 6.0-mm endotracheal tube into the CCT and confirm placement	6. Secure ETT without dislodging tube	7. Perform entire procedure within 1 minute
1	Determine CCT is necessary							X
2	Palpate the thyroid cartilage and move down to the space between thyroid and cricoid cartilage and in addition palpate from the sternal notch to identify the cricoid cartilage to confirm landmarks	X						X
3	Perform incision with blade scalpel (#10, #11, or #15).		X					X
4	Create a 4–5 cm midline vertical or a horizontal incision through the skin to the cricothyroid membrane.		X	X				X
5	• Horizontal cricothyroid membrane incision • Make horizontal incision at lower aspect of membrane • Immediately place finger or clamp through incision into airway to hold position open		X	X				X
6	Use finger, Kelly clamp or tracheal dilator to dilate the incision			X	X			X
7	Insert the ETT in to the trachea.					X		X
8	Advance the ETT far enough to ensure the cuff is within the trachea then inflate cuff.					X	X	X
9	Inflate the cuff with air.					X	X	X
10	Confirm tube placement					X	X	X
11	Secure the tube with sutures to the neck.						X	X

CCT = cricothyroidotomy.

Table 4 Identifying the key landmarks for performing a CCT and scoring

Proper identification of	Scoring
Thyroid notch	5
Cricoid cartilage	5
Cricothyroid window/membrane	5
Only hyoid bone	1
Only sternal notch	3

boogie is used to advance ETT within trachea, it should be extracted before inflating the cuff to less than 20 mm hg. The task is completed when the cuff is inflated, and the ETT is connected to a breathing unit. In the verification task, the tube placement is confirmed by connecting the ETT to a breathing circuit or an ambu bag and checking the lung inflation to confirm the pulmonary ventilation and using carbon dioxide detector.[19] After the ETT is verified, the tube is secured to the neck with sutures.

Identification of operative errors

The operative errors most significant for patient morbidity and mortality were identified via literature review, and then confirmed through expert consensus among participating surgeons. Table 2 summarizes these possible complications.

Learning objectives

We defined 7 learning objectives for CCT, listed in Table 3. The objectives start with the identification of landmarks, and end with the completion of the overall procedure within a 1-minute time frame. We mapped each task to at least one learning objective. Some tasks (eg, ETT insertion) were related to more than 1 objective. Similarly, some of the learning objectives such as insertion of ETT tube or entering the cricothyroid membrane involve multiple tasks. The task and learning objective association are indicated with **X** in the Tasks-Objectives matrix in Table 3.

Table 5 Performing an appropriate skin incision and scoring

Technique	Scoring
Length of incision	
>5 cm	3
3–5 cm	5
<2 cm (will require additional cut, FI)	0 (fail)
Depth of incision	
Pierces skin	5
Orientation of incision	
Vertical incision	5
Nonvertical incision	3
Location of incision	
Midline of the neck starting overlying the thyroid cartilage extending inferior to the cricoid cartilage	5
Midline of the neck starting superior to the thyroid cartilage but extends down to approximately 3 cm	3
Incision is not made over the cricoid cartilage	0

FI = failed incision.

Table 6 Entering the cricothyroid membrane and scoring

Possible outcomes	Scoring
Incision enters cricothyroid membrane only	5
Incision enters cricothyroid membrane and penetrates esophagus, or Incision enters cricothyroid membrane and penetrates the trachea a 2nd time or incision enters proximal trachea, or incision does not enter the cricothyroid membrane	0
Incision does not enter cricothyroid membrane, which the learner notices and makes a 2nd incision that enters the cricothyroid membrane	3

Performance scores

We defined a scoring system for each learning objective, based on the priority of the individual task. The best and/or preferred action was scored as 5, an acceptable but less ideal as 3, and a failing maneuver was given a score of zero. The tasks and rubric are shown in Tables 4–10.

Timing analysis

In the timing analysis, we studied each video frame by frame using Windows and VideoLAN Client media players. Time points for each subtask were measured using specific guidelines, with start and end times as listed in Table 1. Along with the task times, observers were asked to score the tasks based on the defined rubric in Tables 4–10 Task times and scores from each observer, and overall average time for each task, were collected for statistical analysis. Furthermore, inter-rater reliability testing was conducted on each rated subtask using the IBM SPSS 22 software.

Table 7 Dilating the cricothyroidotomy with appropriate tool and scoring

Technique	Scoring
Insert one of the following into the site of incision: scalpel handle, trousseau dilator, Kelly clamp, hemostat, finger	5
Amount of dilation achieved with selected device	
Proper (large enough to fit ETT)	5
Insufficient (not large enough to fit ETT)	1

Table 8 Inserting ETT into cricothyroidotomy, confirming placement, and scoring

Technique	Scoring
Insert small-cuffed tracheostomy tube	
Proper insertion	5
Improper or no insertion	0
Inflate cuff	
Proper inflation	5
Improper or no inflation	0
Check for proper amount of inflation	5
Attach ambu bag	5
Evaluate airway	
Auscultate lungs and stomach or capnography	5
All of the previous events have been performed in the correct order	5

Results

Three observers analyzed all the videos and identified all subtasks' start time, end time, scores, and total time spent over the procedure. All 3 observers are proficient in HTA and have solid understanding of the CCT steps. Some variability arose in the tasks performed in the videos. Of 7 videos, only 2 videos featured use of the tracheal hook during the procedure, whereas the rest used different tools such as a Kelly clamp, a finger, or a Trousseau dilator to dilate the CCT. Finally, the ETT was secured in 3 cadaver videos, but not in the live-patient CCT.

Fig. 3 shows the box plot of task times for the major CCT tasks measured by 3 different observers analyzing the 7 videos. Fig. 4 shows the performance score data for all major CCT tasks. Pearson's correlation tests were conducted to find any correlation between the task times and scores. In the identification of landmarks task, the correlation test indicated a strong positive correlation (R = .8809) between score and procedural time, with a statistically significant result (P = .0204). Likewise, for the insertion task, the correlation test results showed a strong positive correlation (R = .8992, P = .0059). The incision task correlation test result, meanwhile, indicated a negative correlation (R = –.7603, P = .0473) between the task score and time. No other correlations within the data were noted.

Table 9 Securing ETT and scoring

Proper technique	Scoring
The ETT needs to be secured in position using tape or 2 anchoring suture such that it will not be dislodged without the use of excessive force	5
suture(typically 0–2.0 silk or nylon suture)–loosely applied to ETT or suture–applies pressure that extrudes ETT	0
2 anchoring sutures ± tape	5
Just tape	3
1 anchoring suture ± tape	2

Table 10 Performing the entire procedure within 1 minute and scoring

Proper technique	Scoring
Perform entire procedure within 1 minute, otherwise failed	Pass/fail

Among the tasks, securing ETT required the longest amount of time to complete. The average time for this task was 38.7 seconds (min: 33; max: 42). The 2nd most time consuming task was performing the incision, which took an average of 19.9 seconds (min: 6; max: 36) seconds. The insertion task takes average 11.7 seconds (min: 2; max: 21). Identification of landmarks required 7.2 seconds (min: 2; max: 11) on average. The rest of the tasks required less time. The largest variations in time were observed in performance of the incision, insertion of ETT, securing of ETT, identification of landmarks, and hook CCT.

The average score acquired for the incision task was 19.3 (min: 18; max: 20). The incision task has multiple criteria and steps, each associated with points, which increases the maximum attainable score. This is also true for the identification of landmarks task, with an average score 11.2 (min: 4; max: 15). The largest variations in scores were observed in the identification of landmarks, incision, and insertion tasks. The score and time percent's can be seen in Figs. 5–7. The time and point percent in figures are computed with respect to the maximum grade and/or maximum time for each task.

To test the inter-rater reliability for the 3 observers, an interclass correlation coefficient (ICC) was computed for each of the task. ICC was performed to show how items (scores and/or times) in the same category favor each other, by comparing variability to the total variation in all ratings and subjects. Cronbach's alpha test was used to estimate the reliability of objective testing on the same data. There was strong disagreement between the raters regarding proper incision orientation (Cronbach's alpha = .429, ICC = .286, P = .193). There was a significant agreement among the observers for the proper identification of thyroid notch (Cronbach's alpha = .805, ICC = .767, P = .014), which likely arose from inconsistent declaration of landmarks by surgeons in the videos. The remaining tasks showed perfect agreement (Cronbach's alpha = 1.0, ICC =1.0).

According to the grading rubric (Tables 4–10), learners fail in their performance of CCT via 1 of 2 pathways. Either (1) the CCT tasks are performed correctly, but the user takes longer than 1 minute to complete the entire procedure, or (2) the tasks are completed within 1 minute, but one or more of the tasks are not performed correctly. One minute was selected given the time-sensitive nature of the procedure, and the immediacy with which an airway must be established in an emergency. In the recorded videos, the total procedure time often exceeded 1 minute because

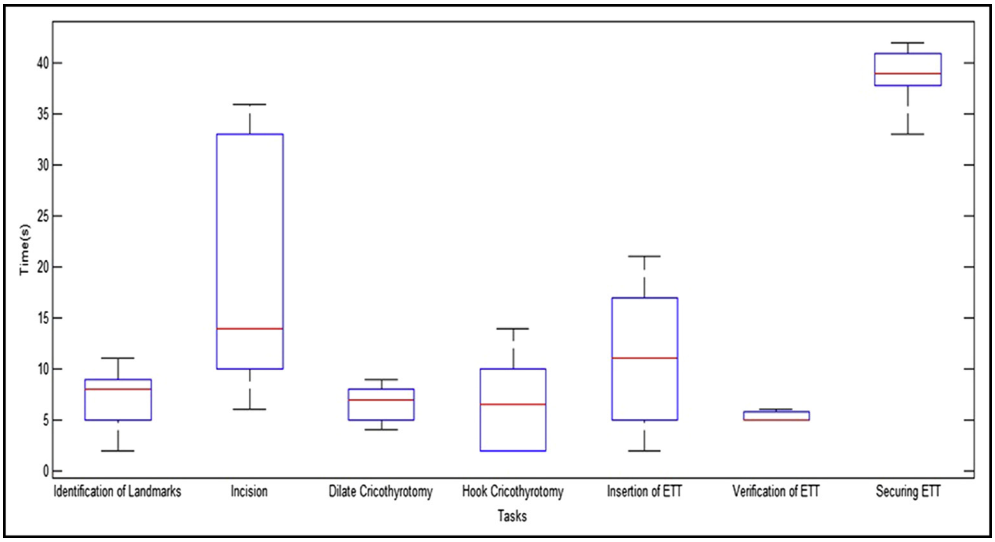

Figure 3 Time series results from the 7 videotaped performances for 7 major tasks for the CCT procedure.

of the instructive narration given by the performing surgeons. To account for this confounder, the total time was calculated by summing the times for each individual task, excluding commentary. In all scenarios, this total time was less than 1 minute.

Although the procedures were performed by expert surgeons, observers noted several of the errors listed in Table 2. One error was failure to locate a key landmark such as the cricothyroid membrane after a skin incision. Expected, such errors were associated with prolonged procedure time and decreased task score. Furthermore, in multiple videos the securing ETT was not completed, which were noted as failure to secure errors. Finally, in multiple recordings, the subjects did not cut the suture after securing the ETT. This was not considered an error; however, it prolonged the overall time.

Comments

The experts used in this study were a group of 7 fellowship trained trauma and acute care surgeons. Each expert has performed over 15 cricothyroidotomies in the last 5 years and regularly trained residents on cadaver models.

In this preliminary phase of development of a VR CCT training simulator, we present a task analysis tree outlining the entire CCT procedure into 5 main stages, each with several tasks and subtasks. This task analysis allows CCT to be compartmentalized into distinct segments, which can be used for quantitative measurements and feedback in a VR simulator. Since each phase, task, and subtask can be individually mapped to learning objectives for surgical performance, they can be used for monitoring CCT skills

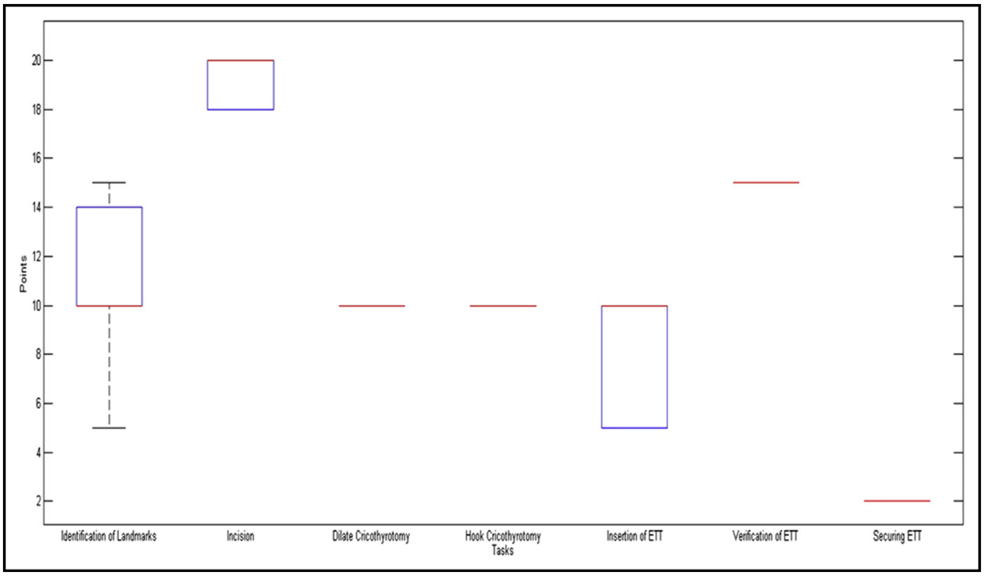

Figure 4 Average grading points of 7 videotaped procedures for 7 major tasks by 3 observers.

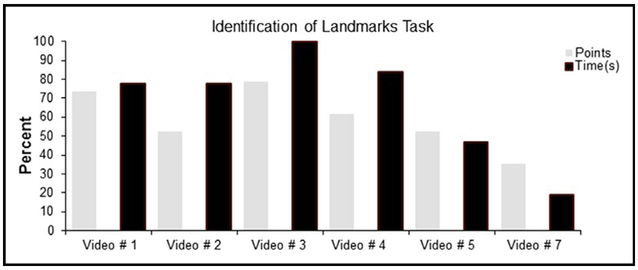

Figure 5 Time and point comparison plot in percent values for the identification of landmarks.

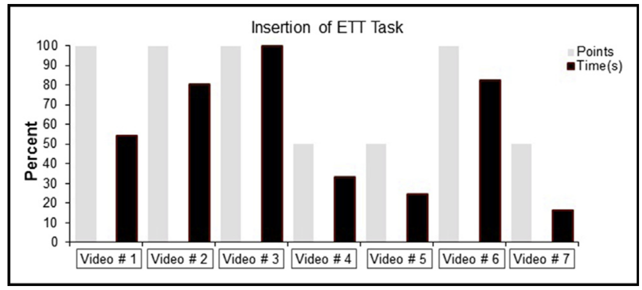

Figure 7 Time and point comparison plot in percent values for the insertion task.

training and assessment. Several features of our task analysis warrant further investigation. As noted in results section, there is a positive linear correlation between times and scores for identification of landmarks and insertion of ETT tasks. In plain terminology, surgeons who did not rush these step had higher degrees of performance accuracy. There was a negative correlation, however, between time and score for the incision task. Although one could postulate that more confident and skilled surgeons perform the incision with greater speed, the correlation itself was weak. Further studies using a greater number of analyzed performances are required to elucidate the significance of this finding.

In addition, the inter-reliability test results showed sizeable disagreement among observers in grading the orientation of the incision. The orientation was not accurately identifiable from the videos in all circumstances, and the multiple camera angles created dissimilar scores because of the quality of the videotaping. This rubric will require fine-tuning as the simulator development progresses.

In the videos provided an ETT was chosen over a flanged tracheostomy because of the physicians performing the emergent CCT are often in situations where a flanged #6 tracheostomy is not available. Therefore, it was felt that one should be trained to use an endotracheal tube, although the option to use a flanged tracheostomy is possible.

Under the identification of operative errors, transverse incision was noted as a cause for cutting the anterior jugular veins in the incision phase. Although not a mistake in the model, the vertical midline incision is preferred given the avoidance of cutting the anterior jugular veins. In an emergent CCT, a large midline incision provides ample access to the cricothyroid membrane. The expert group decided this was the preferred approach.

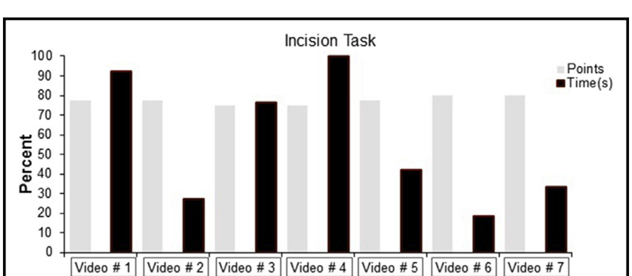

Figure 6 Time and point comparison plot in percent values for the incision task.

Conclusions

We present a HTA for CCT, as a preliminary phase in the development of a VR CCT training simulator. The resultant task tree serves as a tool not only for our simulator, but also potentially in the implementation of other teaching modules focused on the infrequent, but high-stakes CCT procedure.

In future work, we plan to integrate our findings with haptic data, using gloves fused with sensors to monitor movements, force, and pressure exerted during the CCT maneuvers. Using our hierarchical task tree as a guide, we will incorporate these metrics with statistical analysis to create a final rubric for performance assessment in a VR CCT simulator.

Acknowledgments

Authors would like to thank Adam Ryason and Alexander Yu for their contributions in the study. This project was supported by National Institutes of Health (NIH) Grant NIH/NHLBI 1R01HL119248-01A1, NIH/NIBIB 2R01EB005807, 5R01EB010037, 1R01EB009362, and 1R01EB014305.

References

1. Mayglothling J, Duane TM, Gibbs M, et al. Emergency tracheal intubation immediately following traumatic injury: an Eastern Association for the Surgery of Trauma practice management guideline. J Trauma Acute Care Surg 2012;73:S333–40.
2. Davis DP, Bramwell KJ, Vilke GM, et al. Cricothyrotomy technique: standard versus the rapid four-step technique. J Emerg Med 1999;17:17–21.
3. Hart KL, Thompson SH. Emergency cricothyrotomy. Atlas Oral Maxillofac Surg Clin 2010;18:29–38.
4. Wang EE, Vozenilek JA, Flaherty J, et al. An innovative and inexpensive model for teaching cricothyrotomy. Simul Healthc 2007;2:25–9.
5. Tayal VS, Riggs RW, Marx JA, et al. Rapid-sequence intubation at an emergency medicine Residency: Success rate and Adverse events during a two-year Period. Acad Emerg Med 1999;6:31–7.
6. Vissers RJ, Gibbs MA. The high-risk airway. Emerg Med Clin North Am 2010;28:203–17.

7. Simulation in trauma education: beyond ATLS. Injury May 2014;45:817–8.
8. Pettineo CM, Vozenilek JA, Wang E, et al. Simulated emergency department procedures with minimal monetary investment: cricothyrotomy simulator. Simul Healthc 2009;4:60–4.
9. Aggarwal R, Ward J, Balasundaram I, et al. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. Ann Surg 2007;246:771–9.
10. Cho J, Kang GH, Kim EC, et al. Comparison of manikin versus porcine models in cricothyrotomy procedure training. Emerg Med J 2008;25:732–4.
11. Rosser Jr JC, Rosser LE, Savalgi RS. Objective evaluation of a laparoscopic surgical skill program for residents and senior surgeons. Arch Surg 1998;133:657–61.
12. Fried MP, Satava R, Weghorst S, et al. The use of surgical simulators to reduce errors. In: Henriksen K, Battles JB, Marks ES, et al., eds. Advances in Patient Safety: From Research to Implementation. Programs, Tools, and Products, Volume 4. Rockville (MD): Agency for Healthcare Research and Quality (US); 2005.
13. Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance. Ann Surg Oct. 2002;236:458–64.
14. Grantcharov TP, Kristiansen VB, Bendix J, et al. Randomized clinical trial of virtual reality simulation for laparoscopic skills training. Br J Surg 2004;91:146–50.
15. Rosser JC, Rosser LE, Savalgi RS. Skill acquisition and assessment for laparoscopic surgery. Arch Surg 1997;132:200–4.
16. Cannon-Bowers J, Bowers C, Stout R, et al. Using cognitive task analysis to develop simulation-based training for medical tasks. Mil Med 2013;178:15–21.
17. Leikin Jerrold B, Lipsky Martin S. American Medical Association (Ama) Complete Medical Encyclopedia, ISBN:0812991001. Brookvale, Australia: Random House; 2003. p. 419–20.
18. Paix BR, Griggs WM. Emergency surgical cricothyroidotomy: 24 successful cases leading to a simple ‘scalpel–finger–tube’method. Emerg Med Australas 2012;24:23–30.
19. Hamaekers AE, Henderson JJ. Equipment and strategies for emergency tracheal access in the adult patient. Anaesthesia 2011;66:65–80.