Analysis of Body Movement and Gaze Dynamics during Endotracheal Intubation: Comparison of Performance between Experts and Novices

Kosuke Hamabe¹, Soichiro Inoue¹, Shoichiro Takehara², Toru Shimizu³, and Takanari Yoshikawa¹

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Abstract

Background: Endotracheal intubation is a core skill for airway management. With regard to the expertise of endotracheal intubation among physicians using a rigid laryngoscope, the body movement, the head movement, and movement of the gaze during the intubation procedure vary for each physician. This study aimed to test the hypothesis that the duration of endotracheal intubation, head movement, and movement of gaze intra-procedurally differ between experts and novices and assessed these factors using both a motion capture system and eye-tracking system in a medical simulation setting.

Methods: After obtaining institutional approval, individuals who were either novices or experts at endotracheal intubation using Macintosh laryngoscopes were recruited. Body motion and gaze distribution during endotracheal intubation of a mannequin were recorded and analyzed using a motion capture system and eye-tracking system. The values obtained were compared between the novices and experts.

Results: The endotracheal intubation time was significantly shorter in experts (21.6 ± 7.6 sec vs 30.4 ± 8.3 sec, p=0.002), and the range of vertical head movement was smaller in experts (13.1 ± 7.7 cm vs 39.2 ± 8.1 cm, p<0.001), with significantly different trajectory, than those in novices. The ratio of downward gazing was significantly higher in experts (99.6 [96.7–100]% vs 32.4[18.8–43.4]%, p<0.001), and that of proximal gazing was significantly higher in novices (78.1 [67.9–85.6]% vs 37.2 [6.4–82.1]%, p=0.011).

Conclusion: Body movement and gaze dynamics during endotracheal intubation with rigid laryngoscope differed between novices and experts. This system is a potential and feasible tool for evaluating the practice of endotracheal intubation.

Key Words

Motion capture, eye-tracking, endotracheal intubation, simulation

Introduction

Safe airway management is essential for patient care in various medical situations, particularly in the fields of anesthesia, intensive care, and emergency medicine. Tracheal intubation is a core skill for the implementation of safe airway management. Competency in laryngoscopic endotracheal intubation is essential for many healthcare professionals¹. endotracheal intubation using a rigid laryngoscope is a complex psychomotor skill that requires spatial hand-eye coordination to be exercised at a distance within a narrow space.

In general, textbooks describe the mechanisms of proper patient positioning, opening of the mouth, insertion of the laryngoscope blade, positioning the tip of the blade, and the direction of application of a lifting force to obtain a view of the vocal cords²³;
however, they do not provide information on the movements of the entire body, head, and eyes. Moreover, clinicians do not pay close attention to these movements during routine practice.

Careful observation during daily clinical practice suggests that the duration and manipulation of the laryngoscope, as well as the head movement and depth of gaze during endotracheal intubation differ among physicians when they are using rigid laryngoscopes; less experienced physicians need more time to visualize the vocal cords, and tend to make less subtle movements.

Motion capture systems and eye tracking technology have been extensively applied to the evaluation of body motion and eye movement in various fields such as health care, manufacturing, marketing, sports, and entertainment\textsuperscript{4–6}. In healthcare, motion capture systems have primarily been used to observe patients, but recently, they have also been used to evaluate medical procedures performed by healthcare providers\textsuperscript{7–10}. With regard to endotracheal intubation, motion capture systems are only used to analyze a few body movements\textsuperscript{11–13}. The eye-tracking system is also applied to evaluate clinical performance\textsuperscript{14–17}. However, there have been no studies that have performed gaze analysis during endotracheal intubation.

This study aimed to test the following hypothesis related to motion capture and eye tracking systems in a medical simulation setting: Novices take time to appropriately visualize the vocal cords for endotracheal intubation, and the head movement and depth of gaze during the procedure differ between experts and novices.

\section*{Methods}

This study was approved by the Institutional Review Board of St. Marianna University School of Medicine (Approval number: 3965). Participants for the study were recruited by means of advertisements and oral announcement to anesthesia residents and physicians from July to September, 2018 at St. Marianna University Hospital. Novices were defined as individuals who had performed endotracheal intubation less than 30 times using a Macintosh laryngoscope, while experts were defined as qualified anesthesia physicians who had performed endotracheal intubation more than hundred times using a Macintosh laryngoscope.

\subsection*{Motion capture system and eye movement tracker}

Motion capture was performed using a system comprised of 10 Prime 13 and 2 Prime 13W cameras and retro reflective markers (Acuity Inc., Tokyo, Japan). This system only identifies coordinates if one marker is consistently captured by two or more cameras. During this study, we used a camera arrangement with full coverage of all participants and the ability to capture all markers.

Tobii Pro Glasses (Tobii Technology Ltd., Danderyd, Sweden) were used to evaluate the gaze movement of eyes, which were irradiated with near infrared rays that travelled from the measuring device to the cornea, based on corneal reflection method. The glasses were also used to evaluate the movement of the eyeball.

Data acquired using the motion capture system and eye-movement tracker were subsequently processed using the core software SKYCOM EYE (Acuity Inc., Tokyo, Japan). This software has the ability to calculate the focal position of the gaze with reference to the body movement as three-dimensional coordinates by simultaneously measuring the body and gaze movements (Fig. 1).

\subsection*{Experimental procedure}

All motion capture sessions in this study were conducted in the Simulation Laboratory at the St. Marianna University School of Medicine. Information on the study aims was provided to each study participant using a written informed consent form, and informed consent was obtained in writing. The participants were required to wear a body analysis outfit and cap fitted with 27 motion capture retroreflective markers (forehead, neck, shoulders, upper arms, forearms, back, and waist), as well as goggles for gaze analysis (Fig. 2). Markers were also attached to an endotracheal intubation training mannequin (Kyoto Kagaku Co., Ltd., Kyoto, Japan). Before each analysis, the participant was asked to assume the T- pose (Fig. 2) to calibrate the motion capture system. After calibration, endotracheal intubation was performed on the endotracheal intubation training mannequin by each participant using a Macintosh laryngoscope (Blade 3) with three markers on top. Each participant repeated intubation 10 times. The position of the mannequin head was adjusted at the discretion of the participant, and a towel or pillow was placed under the head to achieve the appropriate position.
Motion & gaze analysis in endotracheal intubation

Figure 1. Experiment setup and setting of the three-dimensional coordinates.
Motion capture is conducted with a system comprised of 10 units of Prime 13 and 2 units of Prime 13W camera.
YZ plane: Y axis running vertically from the head to the belly of the participants before tracheal intubation, and Z axis running horizontally from the head to belly of the manikin in supine position. Theta (θ) angle: between the Y axis and long axis of the laryngoscope handle.

Figure 2. A representative participant before the tracheal intubation.
A representative participant wears a motion analysis outfit and cap with 27 motion capture retroreflective markers and goggles for gaze analysis and stands with T-pose as a reference before each procedure.

Measurement and analysis
In this study, time until successful endotracheal intubation was defined as the time from opening of the mouth to removal of the laryngoscope after confirming passage of the endotracheal tube between the vocal cords. The trajectories of motion capture sensors on the sagittal plane of the mannequin (YZ plane) were measured and analyzed. The YZ plane comprised two axes: the Y axis, running vertically from the head to the abdomen of the participants before endotracheal intubation, and Z axis, running horizontally from the head to abdomen of the mannequin in supine position (Fig. 1). The trajectory of laryngoscope manipulation was evaluated using the time course of the theta (θ) angle between the Y axis and long axis of the laryngoscope handle (Fig. 1). The trajectory was divided into 4 phases referring to the evaluation method described by Carlson et al.\textsuperscript{11}: A) Mouth opening and laryngoscope insertion, B) gradual downslope for to visualize the vocal cords with or without a prior steep upslope of the curve corresponding to the insertion of the laryngoscope into the mouth (the period from when the laryngoscope was inserted into the mouth to enable visualization of the vocal cords), C) plateau corresponding to a constant hold of the vocal cord view during placement of the endotracheal tube, and D) removal of the laryngoscope; abrupt change in θ angle from plateau.

The trajectory of the reflective sensor on the forehead at YZ plane was evaluated as a representative value for postural change during endotracheal intubation. The distribution of gaze points at the YZ plane during endotracheal intubation was evaluated: The gaze points of upward gazing and downward gazing were identified above and below the horizontal plane passing the eyes, respectively. The gaze points of proximal and distal gazing were identified at the spaces between Z coordinates of 0 cm and 50 cm and that of beyond the specified range, respectively, since the former space contains the relevant landmarks for endotracheal intubation.

Statistical analysis
Continuous values, time to successful intubation, durations of each phase of endotracheal intubation, and vertical movement of the forehead marker, are expressed as mean ± standard deviations (SD). The continuous variables were analyzed using Student’s t-test following the Kolomogorov-Smirnov test for normal distribution. Non-parametric data and count data are expressed as median [interquartile ranges] and number (%), and analyzed using the Mann-Whitney U and Chi-squared tests, respectively. All statistical analyses were performed with EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), which is a graphical user interface.
for R (The R Foundation for Statistical Computing)\textsuperscript{18}, and p-value of <0.05 was considered statistically significant.

Results

The participants comprised 5 experts and 6 novices. Data on 18 intubations by 5 experts and 19 by 5 novices were considered valid and used for each analysis of the trajectory of laryngoscope manipulation, duration of endotracheal intubation, and head movement. Total intubation time was significantly shorter in experts (21.6±7.6 sec vs 30.4±8.2 sec, p=0.002) (Table 1). In the analysis results, the durations of Phase A and C of experts were significantly shorter than those of novices (4.5±1.2 sec vs 7.1±1.3 sec, p<0.001 for Phase A and 7.8±3.6 sec vs 11.0±4.1 sec, p=0.015 for Phase C). On the other hand, there were no intergroup significant differences in the durations of Phase B and D, respectively (6.6±2.3 sec vs 8.1±4.5 sec, p=0.232 for Phase B and 3.6±1.2 sec vs 4.2±1.0 sec, p=0.0954 for Phase D) (Table 1).

As a qualitative evaluation of the trajectory of laryngoscope manipulation evaluated by the $\theta$ angle, there is a common feature in both groups during Phase B. In all the trials in experts (18/18) and most of the trials in novices (16/19), the $\theta$ angles increased when the laryngoscope was inserted into the mouth (early part of Phase B) and then decreased when the participant drew a downward convex curve to obtain a better view of the vocal cords. Another quantitative observation revealed that the slopes of Phase B tended to be smooth in experts and jagged in novices. When an abrupt repeated change of 10 degrees or more in the $\theta$ angle during Phase B was defined as a jagged pattern, it was observed in 9 out of 19 trials in novices, but only in 2 out of 18 trials in experts. This difference was statistically significant (p=0.0293). Two representative smooth fluctuations of the $\theta$ angle by experts are shown in Figure 3. Figure 4 shows two representative patterns by novices; one is a curve with the features observed in all the experts in Phase B, but has jagged pattern (Fig. 4-i), and the other is a jagged trajectory without the features observed in the experts in Phase B (Fig. 4-ii).

With regard to the head movement, the range of vertical head movement was smaller for experts (13.1±7.8 cm vs 39.2±8.1 cm, p<0.001) than for novices (Table 1). Back-and-forth head movement was observed for both experts and novices; however, small vertical movements and a linear trajectory of the head movement was observed for the experts, and large vertical movements and trends of lasso-like loop trajectories were observed for the novices. The ratio of looped to linear trajectories was 3:15 for the experts and 18:1 for the novices, with a significant difference (p<0.001). Accordingly, we determined that a linear trajectory with a little vertical movement is a typical pattern in experts and a lasso-like loop trajectory with a large vertical movement is a typical one in novices and have shown some examples in

Table 1. Intubation Time and Range of Vertical Head Movement during Endotracheal Intubation: Mean ± Standard Deviations (SD)

|                      | Experts | Novices  | p value |
|----------------------|---------|----------|---------|
| Intubation time (s)  |         |          |         |
| Total                | 21.6±7.6| 30.4±8.3 | 0.002   |
| Phase A              | 4.5±1.2 | 7.1±1.4  | <0.001  |
| Phase B              | 6.6±2.3 | 8.1±4.5  | 0.232   |
| Phase C              | 7.8±3.6 | 11.0±4.1 | 0.015   |
| Phase D              | 3.6±1.2 | 4.2±1.0  | 0.0954  |
| Range of vertical head movement (cm) | 13.1±0.0 | 39.2±8.0 | <0.001 |

Total: time from opening of the mouth to removal of the laryngoscope after confirming the passage of the tracheal tube between the vocal cords. Phase A: mouth opening and laryngoscope insertion, Phase B: gradual downslope to visualize the vocal cords with or without prior steep upslope of the curve corresponding the insertion of the laryngoscope into the mouth, Phase C: plateau corresponding to a constant hold of the vocal cord view during placement of the endotracheal tube, Phase D: removal of the laryngoscope; an abrupt change in $\theta$ angle from plateau.

Total intubation time was significantly shorter in experts. Phase A and C were significantly shorter in experts. There was no intergroup difference in Phase B and D.

The range of vertical head movement was significantly smaller for experts than for novices.
Figure 3. Two typical angle change of the laryngoscope in YZ plane (θ angle) by the experts.

Phase A: from mouth opening and intake of the laryngoscope, Phase B: gradual slope for view of the vocal cords with or without prior steep upslope of the curve corresponding to insert of the laryngoscope at the mouth, Phase C: plateau corresponding to a constant hold of the vocal cord view during placement of the tracheal tube, Phase D: removal of the laryngoscope; an abrupt change in θ angle from plateau.

All the changes of θ angles were similar in experts, and especially, there is a common feature during Phase B; the angle increased when the laryngoscope was inserted into the mouth (early part of Phase B) and then decreased with drawing a downward convex curve to obtain a better vocal cords view, until the beginning of Phase C. Two typical changes were shown in above.

Figures 5 and 6.

Regarding the vertical gaze movement, we acquired data from 26 intubations for 4 experts and 35 intubations for 6 novices. Typical transitions of the gaze dynamics in the YZ plane are shown in Figure 7. The gaze was mainly distal and mostly downward throughout the procedure in the experts, whereas the gaze point was scattered horizontally and vertically in the novices. The ratio of downward gazing during the procedure was significantly higher in experts (99.6 [96.6–100]% vs 32.4 [18.9–43.3]%, p<0.001). The ratio of proximal gazing during the procedure was significantly higher in novices (78.1 [67.9–85.6]% vs 37.2 [6.4–82.1]%, p=0.011) (Table 2).

Discussion

In this study using motion capture system and eye tracking devices, we demonstrated that experts have shorter intubation times than novices, and both the head movement and the gaze patterns differed between the two groups.

Previous studies using calculation models have indicated that the intubation learning curve that at-
Figure 4-i, ii. Two examples of angle change of the laryngoscope in YZ plane (θ angle) by the novices.

Phase A: from mouth opening and intake of the laryngoscope, Phase B: gradual slope for view of the vocal cords with or without prior steep upslope of the curve corresponding to insert of the laryngoscope at the mouth, Phase C: plateau corresponding to a constant hold of the vocal cord view during placement of the tracheal tube, Phase D: removal of the laryngoscope; an abrupt change in θ angle from plateau.

Two examples of the trajectory of θ angle in novices are indicated; (i) a curve with the feature observed in all the experts in Phase B, but it has jagged pattern. (ii) A jagged trajectory without the feature observed in all the experts in Phase B.

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We obtained 90% success, or achieved a 90% probability of good intubation in the operating room required 57\(^1\) and 47\(^1\) attempts, respectively. These studies were conducted in a clinical setting, and the atmosphere and the condition of patients were different from those under simulation with a mannequin. We defined a participant who had performed fewer than 30 endotracheal intubations using Macintosh laryngoscope, as a novice. Few studies to evaluate the practitioner’s postural changes during endotracheal intubation using motion capture system are reported in the literature\(^1,12\), and there is no study of gaze analysis during endotracheal intubation using eye tracking system. To the best of our knowledge, this is the first study with simultaneous motion and gaze analyses.

Our results showed shorter time of entire intubation procedure for the experts, which is an expected finding and in agreement with those of a simulation study using motion capture system in a mannequin by Carlson et al.\(^11\). However, the authors had divided the procedure into 4 phases, but did not report the duration of each phase. Our analysis on the duration of each phase of endotracheal intubation revealed that the time to insert the blade of laryngoscope and the duration of holding of the view of the vocal cords were longer in the novices, while the time to achieve
visualization of the vocal cord (Phase B) was not different between the groups. Quantitative assessment indicated that the trajectories of the laryngoscope during Phase B were varied and jagged in novices, while those of experts were constant to some extent and smooth. It reflects that novices tend to aggressively manipulate the laryngoscope to obtain view of the vocal cords in contrast to the handling by skilled experts.

To the best of our knowledge, there is no study to evaluate the head trajectories during endotracheal intubation. Both experts and novices showed head movement along the Z axis, but the experts made small vertical head movements with a trend of linear trajectory while the novices made comparatively larger vertical head movements with lasso-like looped trajectory; experts may master the form of endotracheal intubation through their practice. Sakakura et al. conducted motion capture analysis and reported that the novices undergo large head acceleration and jerk during endotracheal intubation\(^\text{12}\), which may be related to poor form of the intubation by novices.

The gaze dynamics during endotracheal intubation have not been reported to date. In the field of anesthesiology, Harrison et al. examined the gaze dynamics in ultrasound-guided regional anesthesia using eye-tracking technology, and reported that experts tend to demonstrate fewer fixations and fixate for a longer period of time in the area of interest\(^\text{14}\); whereas, novices tend to shift their gaze more often.

Figure 5. Three typical trajectory of the head movement in YZ plane by the experts. Most of the head trajectories in experts are linear with lesser vertical movement. Typical movements are indicated.
and fix their gaze on multiple locations\textsuperscript{14}, which is in agreement with the findings of the current study on scattered gaze points in the novices. Moreover, the experts looked to longer distances to secure a larger visual field during endotracheal intubation, while the novices seemed to concentrate on a single point of the vocal cords. Unexpectedly, the experts and novices had significant differences in the patterns of vertical movements of the gaze.

Based on the collective results of the intubation time, patterns of laryngoscope movement, especially that of jagged manipulation during Phase B in the novices, trajectory of the head movement, and gaze movement patterns, we assume that novices attempt to achieve clear visualization of the vocal cord by moving their head and gaze point aggressively to compensate for inadequate manipulation of the laryngoscope. The form of linear head trajectory with distant gazing may reflect mastery of hand-eye coordination in experts performing endotracheal intubation. Individual and institutional learning processes are complex and depend on a wide variety of factors\textsuperscript{19} including those of endotracheal intubation with rigid laryngoscopy. Direct observation using checklists and Global Rating Scales (GRS) have been used to evaluate procedural skills in anesthesia, however, development of more objective and concrete evaluation is needed\textsuperscript{20}. Our study highlights that the duration of the entire procedure, as well as that of each component of endotracheal intubation, head trajec-

\textbf{Figure 6.} Three typical trajectory of the head movement in YZ plane by the novices. Almost all of those in novices draw the lasso-like loop with larger vertical movement. Typical movements are indicated.
Figure 7. Typical transition of gaze dynamics in YZ plane. Upper panel, Expert; Lower panel, Novice.

The gaze is mainly distal and mostly downward throughout the procedure in the experts, whereas the gaze point is scattered horizontally and vertically in the novices.

Table 2. The Ratios of Looking Downward and Proximal during Endotracheal Intubation: Median [Interquartile Range]

|                          | Experts       | Novices       | p value |
|--------------------------|---------------|---------------|---------|
| The ratio of looking downward (%) | 99.6 (96.7-100) | 32.4 (18.8-43.4) | <0.001  |
| The ratio of looking proximal (%) | 37.2 (6.5-82.1) | 78.1 (67.9-85.6) | 0.011   |

The ratio of downward gazing during the procedure was significantly higher in experts. The ratio of proximal gazing during the procedure was significantly higher in novices.

Our study had several limitations. First, the sample size was relatively small, and whether the results can be generalized remains unclear. Second, the outfits with marker used for motion analysis and goggles for gaze analysis physically interfered with the participant’s body movement, particularly in the novices. Third, our experiments were conducted in a simulated environment using a mannequin. Simulation studies differ from the environment in the actual operating-room, and may have affected participant performance, especially in the novices. Implementation of the approach in patients under general anesthesia in the operating room is required to clinically validate the current results. Fourth, the experiments were conducted on a bed with fixed height, which may have affected the head movement. Finally, the movements were analyzed only in the YZ plane; endotracheal intubation is a three-dimensional movement, and move-
ments in the other planes may affect the results. Further study to analyze the movement pattern in three dimensions is needed.

In conclusion, this is the first study to utilize both motion capture and eye tracking analyses for comparison between experts and novices in endotracheal intubation using Macintosh laryngoscope. The experts achieved shorter intubation times than the novices, and the novices made more vertical head movement and frequently gazed at a closer distance, which indicates significant differences of the head movement and gaze patterns between the experts and novices. This system showed potential as a feasible tool for evaluation of the practice of endotracheal intubation.

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Conflicts of Interest

The authors have nothing to disclose.

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