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Methodology to Identify Systemic Vulnerabilities to Human Error during General Anesthesia Administration

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Abstract

This paper presents a methodology to identify systemic vulnerabilities to human error during general anesthesia administration. In collaboration with anesthesiologists, a human factors engineering team developed a process hierarchy of general anesthesia administration for laparoscopic cholecystectomy (removal of the gallbladder). The process interrelationships were modeled with Integration Definition Language Ø (IDEFØ). Detailed task analyses were systematically performed for endotracheal intubation, a critical aspect of airway management. Applying a database of generic human errors, specific human errors that might occur during intubation tasks were identified and quantified in terms of occurrence likelihood, consequence, and detectability. Defense mechanisms were developed for the highest priority vulnerabilities.

Keywords
Human Factors, Health Care, Anesthesiology, Process Models, Vulnerability Analysis

1. Introduction

Administration of general anesthesia, similar to other complex human-machine system processes, relies considerably on the performance of the responsible human operator, in this case, the anesthesiologist or anesthetist. While reliability with respect to patient safety is very high, there always exists the possibility of human error during anesthesia administration. Whether that human error propagates into a consequential event is dependent on the robustness of the human-machine system. This paper presents a methodology to identify systemic vulnerabilities to human errors and applies it to the administration of general anesthesia for laparoscopic cholecystectomy (surgical removal of the gallbladder). Based on this detailed task analysis, defense mechanisms are developed for one critical aspect of anesthesia administration to improve the robustness of the human-machine system.

A project team of human factors engineering students and faculty at Oregon State University extended a protocol methodology for identifying systemic vulnerabilities for laparoscopic cholecystectomy [1] to general anesthesia administration during laparoscopic cholecystectomy. The project team collaborated with anesthesiologists as subject matter experts to develop a process hierarchy model for general anesthesia administration. The process hierarchy model was validated and supplemented by direct observations by the project team in hospital operating rooms. Using this framework, the project team modeled the process with Integration Definition Language Ø (IDEFØ) [2] to include processes, inputs, outputs, controls, and mechanisms, as well as process interrelationships. Detailed task analyses were systematically performed for endotracheal intubation (insertion of a breathing tube into the trachea), since this activity is a major cause of patient mortalities with respect to airway management. Applying a database of human fallibilities and generic human errors, the project team identified specific human errors for intubation tasks and quantified consequences of these potential human errors in terms of likelihood of occurrence, severity of consequence, and difficulty of detection. Finally, defense mechanisms were developed to reduce systemic vulnerabilities due to potential human errors for the highest priority vulnerabilities during intubation tasks.

The following sections present the details of how the project team performed each of the above steps.

2. Process Modeling

The first step of the modeling focused on the development of a process hierarchy of the different processes or activities to administer general anesthesia for laparoscopic cholecystectomy. Applying an approach similar to hierarchical task analysis [3] [4], the resultant process hierarchy consisted of the most general processes at the highest level with more detailed processes, sub-processes, and tasks provided at subsequent lower levels. Consistent with IDEFØ modeling [2], the maximum number of processes was limited to six activities at each level and named with active verb phrases.

The resources for establishing the draft process hierarchy were interviews with one subject matter expert, references to anesthesia text books, and anesthesia standards maintained by the American Society of Anesthesiologists [5]. The first complete draft of the process hierarchy was subsequently reviewed by a second subject matter expert. The draft process hierarchy greatly facilitated the interview with the second subject matter expert in terms of providing a visual framework with shared terminology for the systematic review.

Supplementing the interviews with the two subject matter experts, the project team conducted observations of the administration of anesthesia in operating rooms at three different hospitals. Again, the process hierarchy greatly facilitated the project team members becoming knowledgeable in the anesthesia domain. In turn, this allowed the project team observers to be able to appreciate and understand the details in order to ask pertinent questions about the process.

Part of the final process hierarchy, which formed the basis of the IDEFØ node tree, is provided in Figure 1.

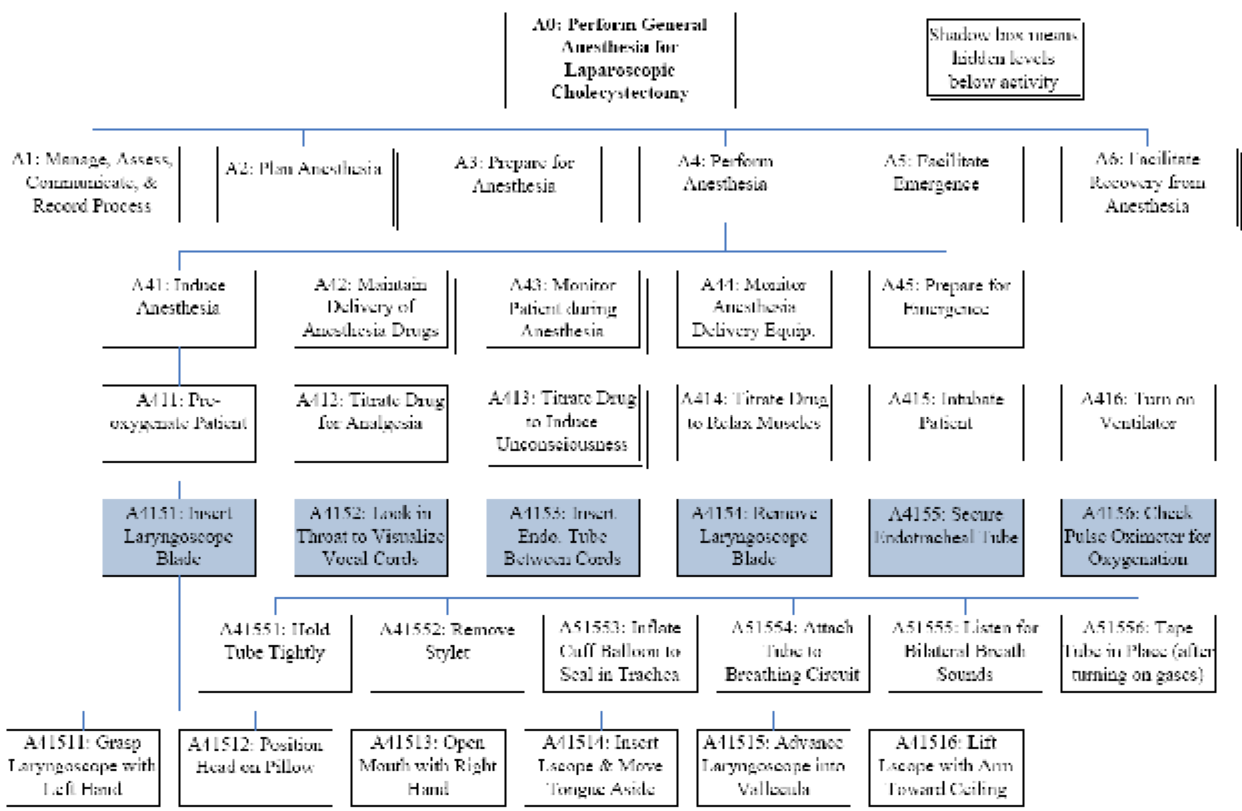

Figure 1: Final process hierarchy for general anesthesia administration

In Figure 1, "A" denotes "activity", the IDEFØ term for a process with the following numerical index identifying the activity and indicating the level of the activity. The highest level of process activities to perform general anesthesia for laparoscopic cholecystectomy was determined with the subject matter experts to be activities A1 through A6. The A2 activity to plan anesthesia was separated from the A1 activity, since planning anesthesia is a distinct process which includes the patient interview and is covered by a standard for pre-anesthesia care [5]. The process hierarchy shown in Figure 1 is a partial representation of the hierarchy in that it decomposes the A4 activity to perform anesthesia to reach the task levels for the A415 activity to intubate the patient. The shadow box indicates more levels are below the shadowed activity but are hidden in Figure 1.

An IDEFØ process model was then developed with AIØ WIN® software [6] to model the inputs, outputs, controls, and mechanisms for the process activities. Equally important was the inclusion of process or task interrelationships, which are not indicated in the process hierarchy model and therefore limit that model's effectiveness for error analysis. The IDEFØ model is shown in Figure 2 for the six shaded activities in Figure 1 which represent the A415 activity to intubate the patient. The first three activities are expanded in the bottom of Figure 2 for readability. The complete IDEFØ model may be obtained by e-mailing one of the authors at funkk@engr.orst.edu.

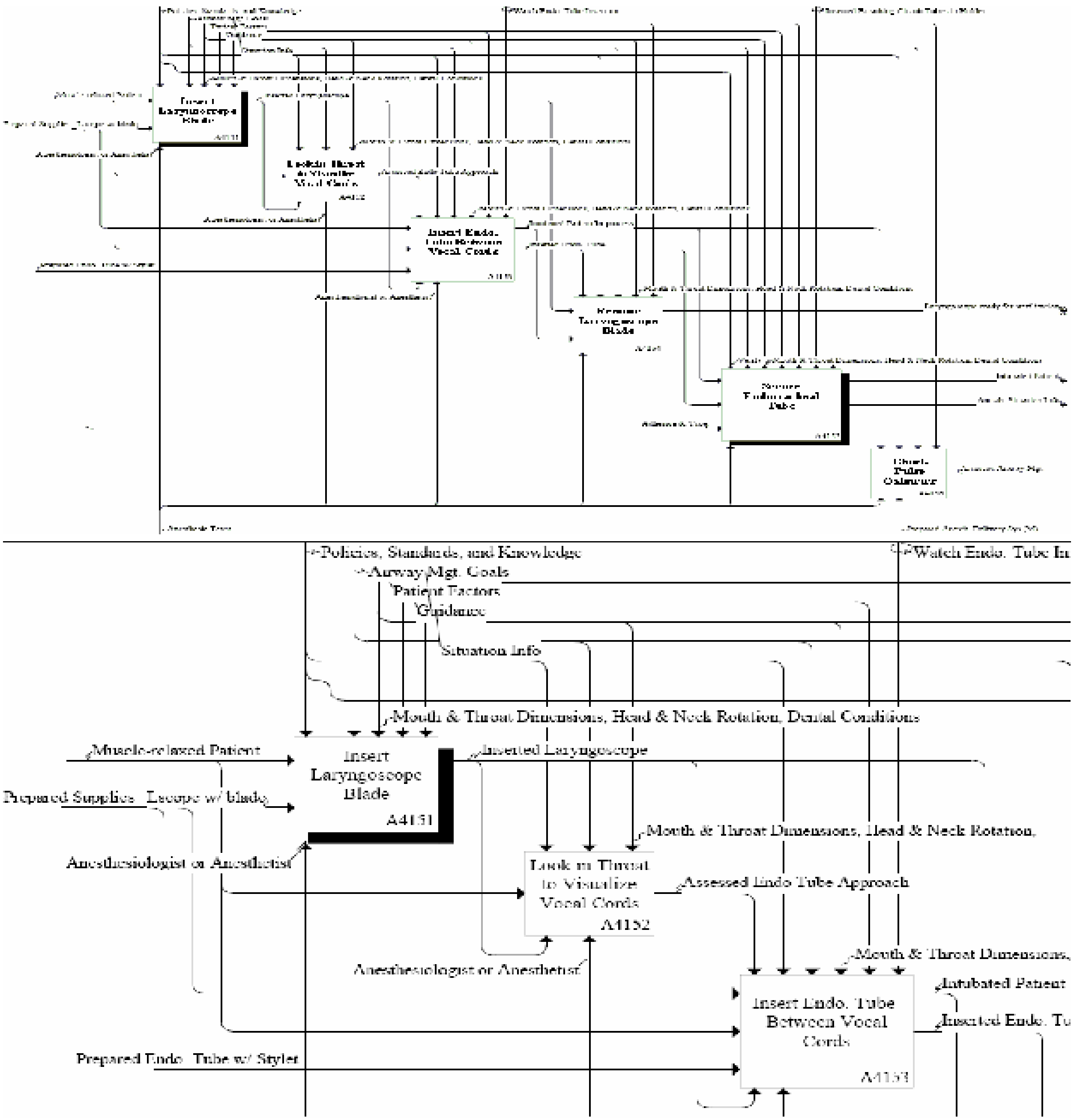

Figure 2: IDEFØ process model for A415 activity to intubate patient

The purposes of the IDEFØ process modeling, and the resulting model itself, are to understand and document the administration of general anesthesia for laparoscopic cholecystectomy to improve patient safety by identifying system vulnerabilities to human errors. The viewpoint of the IDEFØ model is from a human factors or cognitive engineering perspective with respect to the anesthesia team. In addition, the project team prepared a glossary of the specific terms used in the IDEFØ process model for general anesthesia to facilitate communications between human factors engineers and domain experts.

3. Task Analysis

The process models described above were decomposed to a detailed level until the sub-processes became tasks. For methodology purposes, tasks are detailed sub-processes that can be described with simple active verbs and direct objects. At this level, the tasks can be systematically analyzed for human errors and systemic vulnerabilities.

For the administration of general anesthesia, the project team chose endotracheal intubation as the activity for task analysis and subsequent human error identification. The main tasks during endotracheal intubation are inserting the laryngoscope blade into the patient's mouth to view the vocal cords, passing the endotracheal tube between the vocal cords, and placing the end of the endotracheal tube into the trachea. The laryngoscope blade is subsequently removed. Finally, the endotracheal tube is secured after confirming placement of the endotracheal tube by different means, including a check of the pulse oximeter to confirm adequate oxygenation of the patient's arterial blood. In the IDEFØ process model, the endotracheal intubation activity is A415: Intubate Patient and is shown in Figure 2.

The project team focused on endotracheal intubation because correct and timely insertion of the endotracheal tube is one of the most critical airway management tasks during administration of general anesthesia for laparoscopic cholecystectomy. According to a report from the American Society of Anesthesiologists database of closed malpractice claims, esophageal intubation (insertion of endotracheal tube into the esophagus instead of the trachea) and difficult endotracheal intubation accounted for 18% and 17%, respectively, of cases of anesthesia-related death or permanent brain damage [7]. Additionally, dental damage which may occur during endotracheal intubation is one of the most common causes of malpractice suits against anesthesiologists [8].

Table 1 provides a sample of data for the task analysis for intubation. Each task for intubation is broken into an actor (person performing the action), action verb, and direct object. In addition, the action verb from the anesthesia domain is translated into a primary verb contained in the task glossary in the human performance database discussed in the next section. That is, the task analyst, based on input from the subject matter expert and direct observations in the operating room, translates the domain-specific verb into a general primary verb in the database.

Table 1: Potential human errors in the A415: Intubate Patient task. A = Anesthesiologist or Anesthetist. Primary verb and direct object shown in parentheses are obtained from human performance database.

A4152: look in throat to visualize vocal cords					
Actor	**Verb**	**Object**	**Fallibilities**	**Generic Errors**	**Specific Errors**
A	plan (generate)	insertion of endotracheal tube (alternatives)	working memory limits, decision biases, availability heuristic, overconfidence bias, recency bias	generate infeasible alternative, fail to generate plausible alternative	plan fails to consider all alternatives for endotracheal tube insertion and could lead to damage to throat or improper insertion; may not be prepared for difficult airway for intubation due to patient factors

4. Human Error Identification

Using a human performance database containing human fallibilities and generic human errors associated with specific primary verbs, the A415 intubation tasks were systematically evaluated for potential human errors to identify specific human errors that could lead to incorrect endotracheal intubation. These human fallibilities, generic human errors, and specific human errors are included in Table 1 for a specific task associated with planning for endotracheal intubation. In some instances, additional human fallibilities were identified to supplement the human performance database. However in general, the translation from the domain-specific verbs to the primary verbs in the human performance database worked effectively in identifying human fallibilities and potential generic human errors. Of primary importance, this approach ensures a systematic evaluation of all generic errors for human fallibilities associated with each task, thereby reducing the possibility of missing potential errors.

5. Vulnerability Analysis and Results

For the vulnerability analysis, each of the specific human errors for intubation tasks was evaluated with respect to three criteria: 1) probability of occurrence, 2) severity of consequence, and 3) difficulty of detection. Applying a Failure Modes and Effects Analysis (FMEA) approach, each of these three categories were assigned a numerical value ranging from 1 to 10. A higher rating indicates more adverse consequences.

The mathematical product of probability of occurrence, severity of consequence, and difficulty of detection was then calculated to determine an overall priority for the systemic vulnerability analysis. The specific errors with the highest priorities were evaluated to determine where defense mechanisms were most needed. The results of the vulnerability analysis for a specific intubation tasks are provided in Table 2.

Table 2: FMEA for specific planning sub-task shown in Table 1. A = Anesthesiologist or Anesthetist.
Scale for ratings is 1 to 10 with 10 being the most adverse consequence, and priority column is the product.

A4152: look in throat to visualize vocal cords							
Actor	**Verb**	**Object**	**Specific Errors**	**Prob. of Occur.**	**Severity**	**Diff. of Detect.**	**Priority**
A	plan (generate)	insertion of endotracheal tube (alternatives)	plan fails to consider all alternatives for endotracheal tube insertion and could lead to damage to throat or improper insertion; may not be prepared for difficult airway for intubation due to patient factors	4	7	8	224

Considering human fallibilities in the database and applying the above quantitative analysis for endotracheal intubation, the system is vulnerable to the following human errors: 1) failure to anticipate a difficult intubation due to patient factors, 2) insertion of the endotracheal tube into the esophagus rather than the trachea, 3) insertion of the endotracheal tube into one of the lungs, 4) damage to the teeth due to improper laryngoscope blade insertion, and 5) damage to the throat tissue due to laryngoscope blade or endotracheal tube insertion. While the potential for these errors may be obvious to an anesthesiologist, this methodology allows the human factor engineers to develop defense mechanisms for the particular human fallibilities and specific errors associated with the tasks for endotracheal intubation. Table 3 lists a sample of proposed defense mechanisms developed by the project team.

Table 3: Defense mechanisms for specific planning sub-task shown in Tables 1 and 2.
A = Anesthesiologist or Anesthetist.

A4152: look in throat to visualize vocal cords			
Actor	**Verb**	**Object**	**Defense Mechanisms**
A	plan (generate)	insertion of endotracheal tube (alternatives)	Procedures: Require all equipment and supplies needed to respond to the worst case scenario be prepared for use in advance. Institute a peer review process for higher risk patients in which the anesthesiologist consults a peer about likely problems for the case. Training: Train to simulations and case studies to improve planning and trouble-shooting for abnormal cases. Technology: Develop adaptive automation computer program which considers all patient and relevant non-patient factors to develop and present alternatives for anesthesiologist to consider; anesthesiologist has final responsibility for plan.

6. Conclusions

As part of an ongoing collaboration between human factors engineers and anesthesiologists to improve the safety of anesthesia, we showed how the use of a prototype methodology [1] might decrease the risk of complications during administration of general anesthesia for laparoscopic cholecystectomy. A modeling framework was presented in which human factors engineers and medical domain experts can work together and communicate with common terminology. In addition, a quantitative method was applied to systematically determine highest priority human errors based on likelihood of occurrence, severity of consequence, and difficulty of detection. Applying a database of human fallibilities and generic human errors to a rich model of the process to determine specific human errors for each task ensures a systematic approach and evaluation, thereby reducing the potential of missing human errors. While many of the human errors identified in this study are known, this methodology offers greater and shared insights for human factors engineers and medical domain experts. Additionally, this approach provides a methodology to anticipate errors in new medical procedures before much operational experience is gained.

This project suggests this methodology can be applied to enhance patient safety as well as improve outcomes in other health care domains. Further testing and validation of this project methodology are warranted.

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